2008

Hydrogen energy: a study of the use of anaerobic digester gas to generate electricity utilizing stand-alone hydrogen fuel cells at wastewater treatment plants

Charles W. Emerson

Rochester Institute of Technology

"Hydrogen Energy: A Study of the Use of Anaerobic Digester Gas to Generate Electricity Utilizing Stand-Alone Hydrogen Fuel Cells at Wastewater Treatment Plants"

By Charles W. Emerson

Completion: Fall 2007

Graduate Thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Environment, Health & Safety Management

Department of Civil Engineering Technology,
Environmental Management & Safety
Rochester Institute of Technology
Rochester, NY

Approved by:

____________________________________ __________

John Morelli, PE, Ph.D., Thesis Advisor — Date

____________________________________ __________

Abi Aghayere, Ph.D., P.E., Department Chair — Date

REPRODUCTION PERMISSION STATEMENT

"Hydrogen Energy: A Study of the Use of Anaerobic Digester Gas to Generate Electricity Utilizing Standalone Hydrogen Fuel Cells at Waste Water Treatment Plants"

By Charles W. Emerson

I, Charles Emerson hereby grant permission to Wallace Library of the Rochester Institute of Technology to reproduce my thesis in whole or in part. Any reproduction will not be for commercial use or profit. In addition, if the reader obtains any assistance from this volume, he or she must give proper credit in his or her own work.

Signature: ____ Date:______________

ACKNOWLEDGEMENTS

I would like to thank Doctor John Morelli, my thesis advisor, for his direction and continued guidance throughout this project. I would also like to express my appreciation to my thesis committee members, Doctor Jamie Winebrake, professor at Rochester Institute of Technology, and Michael Verde, JD, legal review and technical consultant at Waste Technology Services, Incorporated. I appreciate the time my thesis committee members have sacrificed to support, and participate in this thesis.

I am thankful to my wife Beth for her patience, understanding, and assistance throughout this thesis. Her support, encouragement, and of course, proof-reading, was integral to the completion of this document and my Master of Science degree.

I would also like to acknowledge the contributions of John Trocciola, who spent 41 years with United Technologies developing fuel cells and other advanced technologies, Guy Sliker from the New York Power Authority, Homer Purcell and Bob Tierney from United Technologies Power, and John Love and Mark Torpey from the New York State Energy Research and Development Authority. Without the assistance of these gentlemen, the completion of this research would not have been possible.

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

List of Tables

List of Figures

1.0 Introduction

1.1 Statement of Topic

The purpose of this research is to scrutinize the use of anaerobic digester gas (ADG) to generate electricity utilizing standalone modified phosphoric acid fuel cell power plants at waste water treatment plants (WWTPs). Specifically, five publicly owned treatment works (POTWs) in New York City were studied during this research as case studies. ADG is a methane and carbon dioxide rich byproduct generated from the anaerobic digestion of organics as one of the final stages of wastewater treatment. Typically, after leaving the digester vessel, this gas is burned off by a flare to minimize the release of methane into the atmosphere. Alternatively, it is combusted in boilers at these WWTPs to generate heat for the anaerobic digestion process. This following document summarizes the research and conclusions derived from studying the beneficial reuse of this anaerobic digester gas through the utilization of reformers and hydrogen fuel cells.

This study was performed through the triangulation of literature sources with in-depth interviews regarding the topic of ADG fuel cells and hydrogen energy. Beginning in 1997, the New York Power Authority (NYPA) along with the New York State Energy Research Authority (NYSERDA) sponsored the installation of modified PC 25 C Fuel Cell Power Plants, manufactured by UTC Power, at five waste water treatment plants in the greater New York City region. The first project was completed successfully at the Yonkers, New York waste water treatment facility as a demonstration project to verify this technology. Due to the success at Yonkers, and the emissions reductions demonstrated by these power plants, the four other projects were subsequently undertaken to off set emissions. Focused interviews were undertaken with key stakeholders of this technology.

These five projects were studied in order to determine:

- A cost assessment of the installation and utilization of ADG fuel cells at WWTPs. Is this technology a financially viable solution? Can WWTPs implement this technology without large financial grants from the government?
- What improvements can be made to make the use of this technology more: 1.) Cost effective, 2.) User friendly, and/or 3.) Environmentally friendly?

With the movement in business towards environmental stewardship, sustainability is becoming an important aspect of business and government. Energy consumption will be a major dilemma for future generations. As a proponent of environmental stewardship, it is a duty of the environmental manager to be involved with the energy consumption and conservation programs at his or her institution. Furthermore, it is the duty of the environmental manager to find ways to minimize waste and add value whenever possible.

1.2 Significance of Topic to Environmental, Health and Safety

"Ex-Saudi Oil Minister Sheikh Yamani is the latest of several energy experts to say that 'the Stone Age did not end because the world ran out of stones, and the Oil Age will not end because the world runs out of oil'" (Lovins, "Energy Forever").

Today, environmental issues are becoming increasingly integrated into business decision-making and core business practices. Due to the high costs of environmental excellence, the input and steadfastness of the Environmental Manager is valued in the business environment. Energy supply is an environmental issue facing all sectors of global business. Energy consumption not only has an influence on the monetary bottom line, it also has environmental implications. The job description of the twenty-first century Environmental Manager includes engaging in energy usage issues and promoting environmental stewardship. The international demand for energy is increasing. This is largely due to the fact that many underdeveloped countries, such as China and India, are rapidly industrializing. World population is exponentially increasing. Eighty percent of all commercial energy on Earth is provided by fossil fuels (Bossel). Non-renewable energy sources are diminishing at a rapid pace. Political instability superimposed on these issues has been a constant concern in many petroleum producing countries. Governed by the fundamental economic relationship of supply and demand, the price of energy has been increasing with these trends.

The Environmental Manager must establish energy conserving measures and take advantage of value added beneficial reuse opportunities at his or her business to minimize the impact on profits and to legitimize his or her position. Also important is the environmental stewardship aspect of energy consumption and supply. By definition, environmental stewardship implies continuous improvement of environmental performance to achieve measurable results and sustainable outcomes (Shaw 1). Emissions from fossil fuel usage degrade air quality around the world and produce greenhouse gases. Nuclear power plants represent radiation hazards to the ecosystem and produce radioactive wastes that can not be neutralized. As a steward of the environment, it is the responsibility of the Environmental Manager to not only minimize energy usage at his or her business, but to explore affordable, cleaner, and more environmentally friendly ways to meet the energy needs of the company. With an increased focus on sustainability in business, energy consumption and environmental repercussions from using the energy must be examined by the Environmental Manger. As the price of energy increases, the cost-benefit of instituting alternative energy sources is becoming, and will continue to become apparent.

Clean energies such as electricity from solar, wind, and water must be applied to produce clean hydrogen, without greenhouse gases or nuclear waste being generated in the production process (Bossel). When partnered with a renewable form of energy, hydrogen presents promising potential to meet the energy needs of businesses and all stationary infrastructures.

Many advances have been made in instituting hydrogen energy technologies in New York State. According to the New York State Hydrogen Energy Roadmap, published by the New York State Energy Research and Development Authority (NYSERDA) in 2005, fifty-six hydrogen demonstration projects representing nearly eighty million dollars in investment have been established for stationary infrastructure. These projects have been implemented at colleges, industrial facilities, and, most importantly to this research proposal, utilities. There are a wide variety of hydrogen technologies utilized at these facilities. One commonality among the projects is that the majority of the fuel cells being implemented reform organic fuels (methane/natural gas, methanol, and propane) to liberate hydrogen that is consumed to generate electricity. Preliminary study of work being done by State and Federal Government demonstrates that the pairing of hydrogen fuel cells with hydroelectrolyzers that are energized solely by a renewable energy source (wind, solar, etc.) is still far in the future. This will be discussed more in the concluding paragraphs of this thesis report.

1.3 Reason of Interest

As a student at the University of Rochester, in May of 2002 I completed a dual degree in Environmental Studies and Economics. My thought process as a student was to choose two areas of interest that compliment each other well. One environmental topic which has a great impact on the economy is energy. From an enviro-economist's perspective, it appears that the world will be entering into an energy crisis in the next twenty to fifty years. There will be significant impacts on businesses, the economy, and society. I believe strongly that the level of investment in developing technologies is based upon the demands of society and potential for return. Due to our reliance upon fossil fuels, and the exponentially increasing demand, the price of fuel has been sky-rocketing. Society will soon be approaching the point where the price of energy has increased to the position where the demand is high enough for the economically feasible development of an alternative fuel source.

It is my viewpoint that hydrogen when partnered with fuel cells is a partial solution to this energy dilemma. When aligned with a renewable power source, hydrogen is ideal for the storage and the generation of energy. According to John Heywood, director of MIT's Sloan Automotive Lab, "If the hydrogen does not come from renewable sources, then it is simply not worth doing, environmentally or economically" (Mulik). Over the next 25 years society must significantly increase the use of renewable fuel sources, especially hydrogen, for sake of the economy and the environment. Additionally, as Robert Hefner of the GHK Company illustrates, "Since the mid-nineteenth century, the world has been slowly shifting from one form of energy to another—from solids to liquids to gases" (Dunn 13). The natural progression in the evolution of energy sources is a movement towards fuel source based upon the use of a renewable gas.

From an environmental perspective, there are numerous adverse effects from a global reliance upon non-renewable forms of energy, such as the production of greenhouse gases, air pollution, acid rain, oil spills and water pollution, deforestation, radioactive wastes, foreign energy dependence, and the risk of international conflict over energy.

Hydrogen, when partnered with a renewable form of energy, produces water vapor when consumed. This results in an environmentally friendly energy source. Hydrogen energy may also be implemented to generate electricity while minimizing more influential greenhouse gas releases, primarily methane, from the decomposition and digestion of organic matter.

Much focus has been dedicated to the development of hydrogen fuel technologies for mobile sources (automobiles, planes, etc.). Energy for stationary infrastructure represents a significant fraction of the world's energy needs. It is my opinion that the global society needs to instate hydrogen as a fuel source for all energy consuming applications, including stationary infrastructure.

I believe that it is an important duty of the Environmental Manager to promote environmental stewardship and sustainability, not only within the walls of his company, but to demonstrate to the community the significance of improving and sustaining the environment. It is also a responsibility of the environmental manager to help minimize the use of natural resources by beneficially reusing process byproducts, essentially finding value in waste. As an environmental professional that works primarily with hazardous wastes and industrial byproducts, this topic and thought process is obligatory to my daily job functions.

1.4 Limitations

The use of hydrogen as an energy carrier and fuel is not a new concept to science. However, the technologies to use hydrogen for the aforementioned purposes are currently being developed. As the demand for energy increases and the world's fossil fuel supply diminishes, mankind will need a renewable, clean, readily affordable, and abundant fuel source. This demand for energy and the environmental impact of using non-renewable fuel sources is initiating a movement towards the development of hydrogen technologies. Due to the relative newness of technologies, and the fact that new technologies are being fabricated, a limitation of this thesis will be the lack of scholarly resources on the topic of the use of hydrogen as a fuel source for stationary infrastructure.

Additionally, the economic aspects of the use of hydrogen as an energy carrier or fuel source will limit this study. The monetary potential derived from safely and efficiently harnessing the heat and power from hydrogen will lead toward process and technology secrecy. As new technologies are invented or expanded upon, much information will be proprietary and not possible to attain.

Due to the lack of infrastructure and the great research costs associated with the advancement of the use of hydrogen as a fuel, many countries will lag behind in the development of this technology. This will be a limitation to the widespread adoption of this cleaner fuel source. The reliance upon the sale of fossil fuels of many countries as the sole financial crutch of their society will hinder the development of these technologies as well. As new technologies are developed to alleviate the world's reliance upon petroleum distillates and byproducts, the Organization of the Petroleum Exporting Countries (OPEC) will adjust the price of crude to meet the lessening demand, therefore encouraging the continued use of crude.

1.5 Description of Terms

For the purpose of clear reader comprehension, the following definitions have been provided to communicate the intended meanings of words and technical terms in this thesis.

Hydrogen Energy will be defined as the usable heat or power derived from using hydrogen, or a hydrogen rich fuel, as the single fuel source (Answers.com).

Hydrogen technologies is defined as the physical tools to use (in a controlled manner) hydrogen as a fuel or energy carrier.

A definition of *energy* for the purpose of this thesis will be usable heat or power (Answers.com).

A definition of a *fuel cell* is a device that uses hydrogen (or hydrogen rich fuel) and oxygen to create electricity (United States Department of Energy).

Electrolysis is defined as a "chemical change, especially decomposition, produced in an electrolyte by an electric current"(Answers.com).

Electrolysis of Water is defined as the process by which hydrogen and oxygen are dissociated through the passage of an electric current. Chemically, it may be defined as: $2H_2O + \text{Energy} \rightarrow 2H_2 + O_2$.

Environmental stewardship is defined as the responsibility of environmental quality shared by all those whose actions affect the environment, reflected as both a value and a practice by individuals, companies, communities, and government organizations. Positive stewardship behavior demonstrates acceptance of this responsibility through the continuous improvement of environmental performance to achieve measurable results and sustainable outcomes (Shaw).

Environmental sustainability is the long-term maintenance of ecosystem components and functions for future generations (Entrix).

Hydrogen appliances are defined as the collective term for devices that produce hydrogen on a small scale, at or near the customer (Lovins, "Twenty Hydrogen Myths" 5).

Anaerobic Bacteria are "bacteria that live and reproduce in an environment containing no free or dissolved oxygen" (Guyer 517).

An *anaerobic digester* is defined as "a large air tight tank in which anaerobic reactions take place. Used for the final treatment of sludge in a wastewater treatment operation, it relies upon acetogens and methanogens to reduce the (sludge) volume by 40-60 percent" (Guyer 517).

A *reformer* is a device that extracts hydrogen from other fuels. Typically the chemical reaction that takes place in the reformer is as follows (Wikipedia.com):
$C_nH_m + n\ H_2O \rightarrow n\ CO + (m/2 + n)\ H_2$
$CO + H_2O \rightarrow CO_2 + H_2$

Volatile Organic Compounds (VOCs) are organic chemical compounds that have high enough vapor pressures under normal conditions to significantly vaporize and enter the atmosphere.

Non Methane Organic Compounds (NMOCs) are a broad category (including VOCs) of organic chemical compounds other than methane, including aromatics, aliphatics, chlorinated compounds, alcohols, ketones, and terpenes (Allen 1997).

The *Net Present Value (NPV)* of a project or investment is defined as the sum of the present values of the net annual cash flows minus the initial investment.

The *Internal Rate of Return (IRR)* is the annualized effective compounded return rate which can be earned on the invested capital, or the yield on the investment. Mathematically the IRR is defined as any discount rate that results in a net present value of zero of a series of cash flows (Wikipedia.com).

Sensitivity analysis is the study of how model output varies with changes in model inputs (Wikipedia.com).

A *point estimate* is a single value (known as a statistic) calculated using sample data which is to serve as representative estimate for an unknown (fixed or random) parameter.

2.0 Background

"I believe that water will one day be employed as fuel, that hydrogen and oxygen which constitute it, used singly or together, will furnish an inexhaustible source of heat and light, of an intensity of which coal is not capable."
– Jules Verne, The Mysterious Island (1874)

The potential combustion of hydrogen gas for energy has been known to science for several hundred years. Henry Cavendish, an English Physicist, recognized hydrogen as a distinct element in 1766 when he poured acid on iron and captured the bubbles that were evolved. Upon further experimentation, when recreating the work of an earlier physicist, Joseph Priestley, Cavendish established that the collected gas was found to be combustible. He discovered that when hydrogen was combusted, the sole products of the reaction were water and energy in the form of heat. Based on this experimentation, he determined that water was a compound made of hydrogen and oxygen.

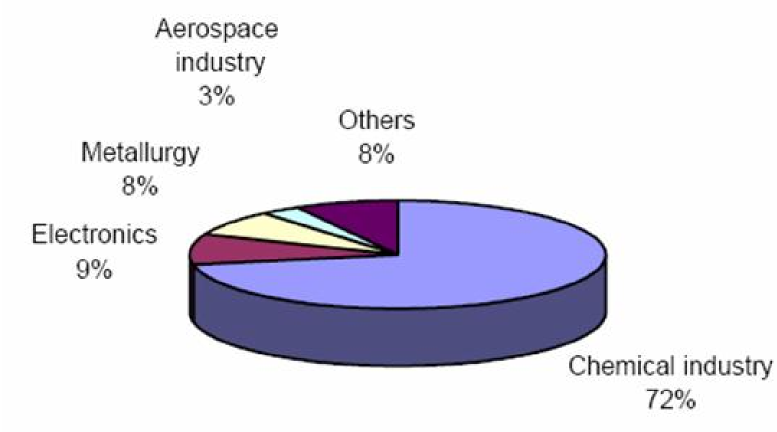
In 1820, Reverend W. Cecil built the first internal combustion engine fueled by hydrogen. Later in the 1800s and during the 1900s, hydrogen engines became increasingly refined to the point that they had become operationally competitive with petroleum-fueled internal combustion engines (Sibelrud; O'Leary). The first hydrogen fuel cell was built in 1839 by Sir William R. Grove (Siblerud; O'Leary). Ironically, the use of hydrogen fuels predated the use of oil. Oil later became prevalent with the invention of the carburetor and because of the ease of production, storage, and fueling (Sibelrud; O'Leary).

The findings of the early work by Cavendish, Cecil, and Grove drive scientists and businessmen towards developing the mobile and stationary infrastructure necessary to cleanly and cost-effectively power the twenty-first century with hydrogen. In the last twenty years, vast strides have been made in developing hydrogen energy. In 1989, the National Hydrogen Association (NHA) was formed in the United States with ten members. Today, the organization has nearly one hundred members, including representatives from the automotive and aerospace industries, federal, state, and local governments, and energy providers. In 1990, the world's first solar-powered hydrogen production plant at Solar-Wasserstoff-Bayern, a research and testing facility in southern Germany, became operational. This marked the first time that a renewable form of energy (photovoltaic) had been paired with hydrogen for the large-scale production of energy. President George W. Bush announced in his 2003 State of the Union Address a $1.2 billion hydrogen fuel initiative to develop the technology for commercially viable hydrogen-powered fuel cells, such that "the first car driven by a child born today could be powered by fuel cells." As of 2005, twenty-three states in the United States have hydrogen initiatives in place to encourage the research and development of hydrogen energy (New York State Energy Research and Development Authority 4). The New York State Energy Research and Development Authority predicts that "in the future (2006-2050), water will replace fossil fuels as the primary resource for hydrogen. Hydrogen will be distributed via national networks of hydrogen transport pipelines and fueling stations. Hydrogen energy and fuel cell power will be clean, abundant, reliable, affordable, and an integral part of all sectors of the economy in all regions of the U.S" (New York State Energy Research and Development Authority 4).

Currently, the production of hydrogen is a large and mature global industry, consuming at least 5% of U.S. natural gas output. Globally, about fifty million metric tons of hydrogen are made for industrial use each year. The U.S. Department of Energy (DOE) reports that about 48% of global hydrogen production is reformed from natural gas, 30% from oil, and 18% from coal (chiefly in China and South Africa for producing nitrogen fertilizer; half the world's hydrogen goes into ammonia-based fertilizer) (United States Department of Energy). Only 4% of the world's hydrogen comes from electrolysis, because that process can compete with reforming fossil fuels only under three main conditions: with very cheap electricity (generally well under 2¢/kWh), if the hydrogen is a byproduct (about 2%, for example, is unintentionally made during "chloralkali" electrolytic chlorine production), or perhaps if the producer is charged for carbon emissions and has a carbon-free source of electricity but no way to sequester (keep out of the atmosphere) carbon released from reforming fossil fuels (Lovins, *Twenty Hydrogen Myths* 8).

Hydrogen is primarily used in the chemical industry (72%), more specifically in petroleum refining (32%), ammonia manufacturing (30%) and the synthesis of methanol (10%). The rest of the hydrogen demand is from small-volume consumers. Electronics companies accounts for 9% of the total hydrogen consumption, the metallurgical industry for 8%, the aerospace industry for 3%, and other types of industries such as glass making and food hydrogenation account for the remaining 8% as it is shown in Figure A ("Draft Business Plan of ISO/TC 197 - Hydrogen Technologies" 4).

Figure A: Consumption of Hydrogen by Types of Application (5)



2.1 Physical and Chemical Properties of Hydrogen

Hydrogen is the lightest element and molecule. Molecular hydrogen (two hydrogen atoms, H_2) has one-eighth the mass of methane (i.e. natural gas). Per unit of energy contained (a ratio of a non-descript unit of energy to the mass, used here for the sake of comparison), it weighs 64% less than gasoline or 61% less than natural gas: 1 kilogram (2.2 lb) of hydrogen has about the same energy as one U.S. gallon of gasoline, which weighs not 2.2 but 6.2 pounds. Per unit of volume, however, hydrogen gas contains only 30% as much energy as natural gas, when held at the same pressure. (Lovins, *Twenty Hydrogen Myths* 2) Even when hydrogen is compressed to 170 times atmospheric pressure (170 bar), it contains 6% of the energy as the same volume of gasoline (Lovins, *Twenty Hydrogen Myths* 2).

Hydrogen makes up about 75% of the matter of the universe, but it is not available as an energy source like oil, coal, wind, or the sun. Alternatively, it is an energy carrier like electricity or gasoline: a way of transporting useful energy to users (Lovins, *Twenty Hydrogen Myths* 1). Hydrogen is an especially versatile carrier because like oil and gas, but unlike electricity, it can be stored in large amounts (often at higher storage cost than hydrocarbons), and can be generated from nearly any energy source and used to provide almost any energy service (Lovins, *Twenty Hydrogen Myths* 2). Its conversion to heat or power is simple and clean (Bossel). Hydrogen is not an energy source because it is almost never found by itself, the way oil and gas are. Because hydrogen has an affinity towards combining with other elements, it is found chemically bound in compounds, such as water, biomass, and fossil fuels. In order to be used, it must first be liberated from its chemical compounds (Lovins, *Twenty Hydrogen Myths* 2). Hydrogen can be produced from water by electrolysis, from the reforming or cracking of hydrocarbon or carbohydrate fuels, or liberated from other hydrogen carriers through chemical processes (Bossel). Certain types of green algae produce hydrogen, as well. Under controlled conditions, biohydrogen can be collected in large quantities from algae.

2.2 Production Methods of Hydrogen

Liberating hydrogen gas from a molecular structure requires energy. A number of options are currently available to produce hydrogen on a large and small scale basis. For the purpose of this research, a brief discussion of each of the major hydrogen production methods will be described in the following paragraph.

Electrolysis is a simple, yet highly energy demanding, process of running electricity through water in the presence of an electrolyte to separate water molecules into its elementary components: oxygen and hydrogen. Thermochemical processes of generating hydrogen involve using the heat from sunlight or advanced nuclear reactors to break the molecular structure of water and produce hydrogen and oxygen gas. The process of using steam to break hydrogen to carbon molecular bonds in natural gas is known as steam reforming. Gasification processes, which are similar to steam reforming, are characterized by the employment of high levels of heat to break hydrogen out of coal and organic matter. Biological processes (including anaerobic digestion) employ organisms to break down water or organic matter to produce hydrogen and oxygen. Steam reforming is the predominant source of hydrogen today, while electrolysis is a well-established technology. The others are at experimental stages (Mazza 1-2).

2.3 Fuel Cells

Inside of a fuel cell, energy is released from the combination of hydrogen and oxygen when forming water. This energy is then converted into a usable form (in the case of stationary sources, heat and electricity).

All fuel cells have three basic components: an anode, a cathode, and an electrolyte that separates them. The hydrogen fuel flows to the anode, where the electrons are removed and transferred to the cathode through an external circuit to produce electricity. Oxygen (or another oxidant) is used at the cathode. When the oxygen, the positively charged hydrogen, and the electrons combine, water and heat are generated as waste, and the process is complete. The location of this chemical combination within the fuel cell, and the exact details of the chemical process vary with the type of fuel cell (Mazza 3). Table 1 summarizes the various types of fuel cells currently available to private citizens and industry. Table 1 also lists the most common use of the type of fuel cell, the electrolyte used, and the temperature at which the type of fuel cell operates.

Table 1: Types of Fuel Cells Currently Available (Mazza 40)

Type	Area of use	Electrolyte	Temperature °C
Alkaline (AFC)	Space travel, transportation	Alkaline	50 – 200
Direct methanol (DMFC)	Transport, mobile equipment	Polymer	80 - 200
Proton-exchange-membrane (PEM)	Space travel, transportation, small CHP, mobile equipment	Polymer	50 – 80
Phosphoric acid (PAFC)	CHP, power plants	Phosphoric acid	190 – 210
Molten carbonate (MCFC)	CHP, power plants	Molten carbonate	600 – 650
Solid oxide (SOFC)	CHP, power plants	Solid oxide	600 – 1,000

As you will notice in Table 1, hydrogen fuel cells are widely used in conjunction with organic reforming units that break down and recombine organic molecules into carbon dioxide and hydrogen. The carbon dioxide is vented to the atmosphere. The hydrogen is then recombined with oxygen through the use of a catalyst in the hydrogen fuel cell to produce water and heat. The most common organic fuel utilized in these fuel cell power plants is natural gas (methane, which is unfortunately a fossil fuel). Fuel cell power plants are being engineered to utilize methane rich gases generated from biomass decomposition and anaerobic digestion processes. Of note, the heat is a valuable byproduct of these fuel cells. Fuel cells are commonly referred to as combined heat and power (CHP) units because of the electricity they generate and the available heat that is generated in the fuel cell. This will be discussed much more in depth later in this document.

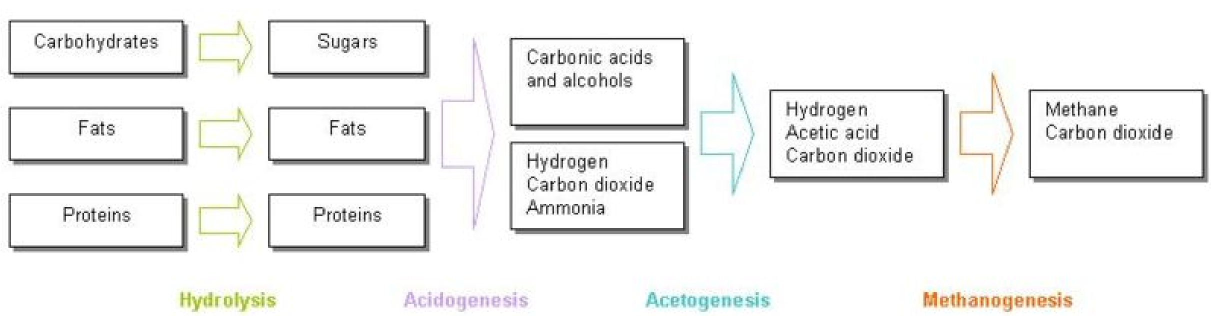
Due to the high cost of natural gas, fuel cell power plants are being engineered to consume methane rich fuels which are generated as the byproducts of decomposition of organic matter such as anaerobic digestion gas (ADG), biomass gas, and landfill gas. Fuel cell power plants are being designed and adjusted to consume these fuels which, in the past, have been combusted in low-efficiency turbines, boilers, and flares. Methanous biogases generated from anaerobic digesters, biomass gasification units, and landfills are similar in composition, but for the purpose of this document, the composition of ADG will be described in detail.

Fuel cell power plants are being utilized as a means to reduce air pollution and offset emissions from the installation of less efficient energy producing technologies, such as coal power plants and gas turbines. Biogases are rarely emitted unaltered to the atmosphere due to their high content of methane. Methane, when released to the atmosphere, is a greenhouse gas twenty to twenty-five times more effective than carbon dioxide at trapping heat within the earth's atmosphere (U.S. Department of Energy, New York Power Authority). Fuel cell power plants can effectively utilize methanous biogases, thus decreasing the amount of methane emitted into the atmosphere or wastefully flared, as well as minimize other harmful emissions of biogas combustion through gas pretreatment. Natural gas, the most common fuel utilized in fuel cell power plants, also contains impurities such as nitrogen, sulfur, ammonia. Fuel cells, due to the sensitivity of the catalysts and membranes utilized in the reforming and fuel cell processes, require these impurities to be removed before a fuel can be effectively converted into energy. Regardless of the source of the fuel being processed in a fuel cell power plant, the gas must be pretreated and harmful emissions are reduced.

2.4 Anaerobic Digestion Gas

Anaerobic digestion (AD) is a process by which bacteria biologically break down organic matter in the absence of oxygen. This process is most commonly employed by farms as a means to control animal wastes and wastewater treatment plants to minimize the amount of solid organic sludge generated from the wastewater treatment process. The focus of this document will be on AD at wastewater treatment plants. AD is a sensitive, multiphase process by which organics chemically undergo hydrolysis, and biologically undergo acidogenesis, acetogenesis, and methanogenesis (Wikipedia.com). The key processes of AD are summarized in Figure B.

Figure B: Summary of the Key Process Stages of Anaerobic Digestion (Wikipedia.com)



Trained technicians are employed by wastewater treatment plants to ensure that the temperature remains between 95 and 145 degrees Fahrenheit and the pH of the vessel remains between 6.5 and 8. Also, the correct mixture and population of bacteria must be present, and the organic feed (load) should be added to the digestion process at a rate that is consumable by the bacteria (California Energy Commission). Optimum temperature, pH, bacteria population, and load requirements will differ between AD processes, but one fact is constant: if there is a disturbance in any of the above parameters, the AD process could not reach completion or completely fail.

There are generally three byproducts of successful AD: nutrient rich organic solids (the digestate), wastewater, and methane rich anaerobic digestion gases. The digestate from AD is typically dewatered and then landfilled, incinerated, or utilized as a fertilizer. The wastewater produced from AD is typically aerated to lower the biological oxygen demand (BOD) and chemical oxygen demand (COD) of the wastewater and discharged with the effluent from the plant. The ADG can be released to the atmosphere, combusted by a flare, or converted into energy utilizing boilers, gas turbines, or specialized fuel cell power plants.

Anaerobic digestion gas is primarily a mixture of methane and carbon dioxide. Methane comprises sixty percent of ADG. Carbon dioxide constitutes approximately 37% of ADG, while the remaining 3% is a mixture of oxygen, nitrogen oxides, sulfur oxides, hydrogen sulfide, carbon monoxide, halides, volatile organic compounds, organic sulfur compounds, and ammonia (Kishinevsky 3-2). Incomplete, or failed anaerobic digestion, could lead to large variances in these compositions. Table 2 (see below) details the analytical results from an ADG grab sample taken in 1997 at the Yonkers, New York wastewater treatment plant.

Table 2: Gas Composition of ADG Sample taken from Yonkers, New York Wastewater Treatment Plant (Kishinevsky 3-2)

Compound	Concentration (%, v/v)		Sulfur Compounds	Concentration (µg/m3)	Concentration (ppb)
Oxygen	<0.60		Hydrogen Sulfide	54,600	39,200
Nitrogen	<2.00		Methyl Mercaptan	216	110
Methane	64.3		Ethyl Mercaptan	508	200
Carbon Dioxide	35.7		Ispropyl Mercaptan	394	126

Carbon Monoxide	<0.40		tert-Butyl Mercaptan	395	107
			n-Propyl Mercaptan	941	302
Ammonia Concentration	**Concentration (ppm)**		**Volatile Organic Compounds**	**Concentration (µg/m3)**	**Concentration (ppb)**
Digestor 1	2.58		Toluene	73,000	19,000
Digestor 2	3.28		Cis-1,2-Dichloroethene	660	170
			Methyl tert-Butyl Ether	620	170

2.5 Availability of Anaerobic Digestion Gas in the United States from WWTPs

The United State Department of Energy (USDOE) estimates that there are 6,850 wastewater treatment plants in the United States that generate large enough volumes of ADG to be considered for energy recovery projects. Of these, the USDOE and the USEPA estimate that 400 of these wastewater treatment plants, all municipal facilities, are good candidates for the installation of ADG fuel cell power plants.

3.0 Literature Review

3.1 The Use of Hydrogen as an Energy Carrier

Many forms of renewable energy sources such as solar power, tidal waters, and wind power cannot provide stability in energy production, and there is often a disparity between the time of production and desired time that the energy is used. Energy systems that are based on these kinds of sources consequently require a means of storing energy, and hydrogen is an energy carrier that is well suited to this (Kruse 6).

Hydrogen is a neutral energy carrier. the environmental benefit of using hydrogen depends upon how the hydrogen is produced. A renewable energy system using hydrogen as a carrier or for energy storage does not result in harmful pollutants being released to the natural environment (Kruse 4). Breaking down water to hydrogen and oxygen is a process that requires energy. Heat, electricity, light, or chemical energy can be used for this purpose. If renewable energy is used, the resulting hydrogen will also be a clean and renewable energy carrier (Kruse 19).

In general, changing energy from one form to another involves inefficiencies in conversion. Research shows that "the overall round-trip efficiency of using electricity to split water, making hydrogen, storing it, and then converting it back into electricity in a fuel cell is relatively low at about 45% (after 25% electrolyzer losses and 40% fuel-cell losses) plus any byproduct heat recaptured from both units for space-conditioning or water heating." Most experts agree that "hydrogen's greater end-use efficiency can more than offset the conversion losses" (Lovins, *Twenty Hydrogen Myths* 11). "The Bumpy Road to Hydrogen" examines the viability of hydrogen and concludes that "hydrogen merits strong support, if only for the absence of a more compelling long-term option." Additionally, its authors ask "… if not hydrogen, then what? No other long-term option… approaches the breadth and magnitude of hydrogen's public good benefits."

Some experts do not believe that hydrogen is the solution to our future energy needs. Hydrogen is a substance with high energy content compared to its weight. However, the energy content compared to volume is rather low. This poses greater challenges with respect to storage compared to storage of gasoline, which is a liquid (Kruse 26). Energy futures such as those including the use of electrical batteries and hydrogen carbon energy have been recommended over the use of hydrogen citing conversion inefficiencies, the lack of infrastructure, cost of the transition to business and society, and safety concerns of utilizing hydrogen as major deterrents. Excerpted from the February 26, 2005 publication, "The Future of the Hydrogen Economy: Bright or Bleak?" the following passage details the recommendations of the authors:

> The time has come to shift the focus of energy strategy planning, research and development from an elemental "Hydrogen Economy" to a "Synthetic Liquid Hydrocarbon Economy". This means directing the limited human, material, and financial resources to providing technical solutions for a sustainable energy future built on the two closed clean natural cycles of water (for hydrogen) and CO2 (for carbon). Fortunately, much of the technology exists already – e.g. for growing biomass, and for fermentation and distillation to produce ethanol. Both methanol and ethanol could be synthesized from water and carbon. Provided that the carbon is taken not from fossil resources ("geo-carbon"), but from the biosphere or recycled from power plants ("bio-carbon"), the "Synthetic Liquid Hydrocarbon Economy" would be far superior to an elemental "Hydrogen Economy", both energetically and environmentally (37).

3.2 Availability of Hydrogen Technologies

Preliminary research has shown that the necessary technology is available to power stationary infrastructure using hydrogen energy. The hydrogen industry has developed ways to build fuel cells economically at all scales, though smaller is often cheaper as well as less vulnerable (Lovins, "Energy Forever" 17). However, most of the hydrogen technologies in the energy sector are either in their development or demonstration phase, and they have not reached commercialization yet. More research is required to address the most critical issues such as increasing the efficiency, reducing the cost of technologies, and ensuring that all the relevant safety issues have been adequately addressed ("Draft Business Plan of ISO/TC 197 - Hydrogen Technologies" 7). Renewable energy technologies (such as wind and photovoltaic) are being improved through research, development, and experimentation. When partnered with renewable energy, hydrogen can be generated on a local or large-scale basis for use as an energy carrier. “Fuel cells are now a viable technology that can readily be put into production, while billions are being spent throughout the world on the further development of this technology. Proton exchange membrane fuel cells (PEM) and solid oxide fuel cells (SOFC) appear to be particularly promising areas of fuel cell development” (Kruse 6). According to the Norwegian Bellona report, “In Norway, hydrogen can be produced locally as a renewable energy source using water electrolysis at a competitive price compared to gasoline, with the added benefit of no greenhouse gas emissions. This is because the production of electricity is almost entirely based (99%) on renewable energy” (Kruse 6). Additionally, large coal-fired and nuclear power plants can be replaced by hydrogen-producing power plants. The existing electrical grid (electrical infrastructure) currently used to distribute energy to homes and businesses can be used to transmit the clean energy generated at these large-scale facilities.

3.3 Policies and Incentives Promoting Hydrogen Energy

> “Even if fuel cells were advanced significantly beyond today’s technology, the United States currently lacks both the physical and regulatory infrastructure necessary to rely on hydrogen gas as a major energy carrier” (Yacobucci 6).

Current consensus in the literature is that the government needs to provide a “catalytic leadership role” in the research, development, and adopted use of hydrogen as an energy carrier (Yacobucci 9). This must be done through federal, state, and local government enactment of policies and incentives, and setting an example by using the technologies they are promoting at government facilities (Yacobucci 9). According to the National Hydrogen Energy Roadmap, published by the United States Department of Energy, policies that foster both technology and market development must be enacted (9).

The rate at which hydrogen emerges will also be shaped by growing energy needs, local pressures on conventional resources, and the continuing quest for more plentiful, available fuels. It will, however, be shaped to a much greater degree by environmental issues as well (Dunn 20-21). In "Energy Forever", the author stresses the importance of innovative thinking by governments when implementing policies and incentives:

> The policy menu need not be confined to an impoverished list of tax tweaks; it can be rich, diverse, expanding, and appealing to all ideological tastes. Outside the transportation sector, we could be teaching architecture, engineering, and business students how to make the most of modern efficiency potential. We could make markets in saved energy, so bounty hunters would pursue it relentlessly. We could mobilize communities to install mass retrofits block by block. We could promote radically fuel-saving businesses that instead of selling more cars and gallons use less of both to provide convenient transportation services. We could scrap inefficient technologies as vigorously as we introduce new ones, rather than further impoverishing poor people and poor nations by selling them our cast-off junk (17).

Currently an array of policies and incentives are established at Federal and State Levels in the United States. These programs include industry recruitment incentives, corporate tax credits, net metering policies, grants, loan programs, rebate programs, personal tax credits, sales tax exemptions, property tax exemptions, and one production incentive (Haynes 2). Federal funding for fuel cells largely supports research and development efforts for both stationary and automotive fuel cell applications, as well hydrogen infrastructure issues. State-level funding, on the other hand, provides more support to the adoption of stationary fuel cells by end-users (Haynes 2). Net metering, a crucial regulatory policy and financial incentive to encourage the adoption of renewable and distributed energy technologies, exists at various levels in thirty-eight states. Net metering allows generators to receive full retail credit for excess electricity produced by eligible facilities (Haynes 5).

The primary argument against American renewable energy policies (including hydrogen energy promotion) is that not enough is being done and that hydrogen plans encourage the generation of hydrogen from non-renewable sources. In Dunn's "Hydrogen Futures", he argues that "Hydrogen has yet to be piped into the mainstream of the energy policies and strategies of governments and businesses, which tend to aim at preserving the hydrocarbon-based status quo—with the proposed U.S. energy policy, and its emphasis on expanding fossil fuel production, serving as the most recent example of this mindset." In addition, "very little has been done to educate people about the properties and safety of hydrogen, even though public acceptance or lack thereof, will in the end make or break the hydrogen future" (12).

Greater international collaboration between governments and markets in supporting hydrogen is needed (Dunn 67). On an international level, members of the European Union are leading the way in promoting the use of hydrogen energy sources. Many European countries, such as Norway, have revolutionary renewable hydrogen energy implementation and usage policies. International organizations, such as the International Standards Organization (ISO) are drafting and implementing international guidelines for using renewable hydrogen energy. The "Scope of the ISO/TC 197 Standardization (is) in the field of systems and devices for the production, storage, transport, measurement and use of hydrogen" ("Draft Business Plan of ISO/TC 197 - Hydrogen Technologies" 2). ISO/TC 197 encourages private and industrial applications of hydrogen energy. "Even though, ISO/TC 197 was created to promote the increased use of hydrogen as an energy carrier and fuel, the existing and new industrial applications should no longer be neglected by ISO/TC 197. These applications would certainly benefit from the implementation of international standards to harmonize the state-of-the-art, hence ensuring a safe use of hydrogen."

3.4 Barriers to the Use of Hydrogen Energy

In addition to weak government policy and incentive, experts cite other barriers prohibiting the use of hydrogen. These include safety and storage issues, lack of public awareness and education regarding hydrogen and the availability technologies, and lack of the necessary infrastructure. Additionally, the current cost of the necessary technology and adjustments to accommodate hydrogen energy is prohibitive. "The cost of hydrogen and its associated technologies is the major barrier to the successful implementation of hydrogen energy systems. The hydrogen basic cost is currently higher than the cost of conventional fuels. Therefore, reducing the cost of hydrogen and its associated technologies is the biggest challenge of the hydrogen industry" ("Draft Business Plan of ISO/TC 197 - Hydrogen Technologies" 7). Some studies have also considered the detrimental environmental impacts of releasing increased water vapor and hydrogen into the atmosphere.

4.0 Case Studies

There are five waste water treatment plants in the greater New York City area that have partnered with the New York State Energy Research and Development Authority (NYSERDA), the United States Environmental Protection Agency (USEPA), the New York Power Authority (NYPA), the New York State Department of Environmental Conservation (NYSDEC), the Electric Power Research Institute (EPRI), the United States Department of Energy (USDOE), and private organizations, specifically United Technologies Power (UTC Power). These entities together have developed and implemented the use of specialized gas pretreatment units, organic reformers, and hydrogen fuel cells to generate electricity from anaerobic digester gas. This is accomplished through the utilization of modified commercial phosphoric acid 200 kW fuel cell power plants to recover energy from ADG which has been cleansed of contaminants (specifically nitrogen oxides, sulfur oxides, hydrogen sulfide, carbon monoxide, halides, volatile organic compounds, organic sulfur compounds, and ammonia) using patented gas pretreatment units (GPU) (Kishinevsky 1997, 3-2). These power plants have been engineered to run parallel to the electrical grid, meaning any electricity needs not supplied to the wastewater treatment plant by these power plants can be purchased from the power grid. These modified PC 25 C units also produce 900,000 BTU of heat per hour or operation at full capacity that can be used onsite for anaerobic digester warming, hot water, and heating buildings. The five locations are summarized in Table 2.

Table 3: Anaerobic Digestion Gas Fuel Cell Power Plant Projects

Facility Name	Facility Location	Number of Fuel Cells	Project Cost*
Yonkers Wastewater Treatment Plant	Yonkers, NY	1	$1,000,000
Red Hook Wastewater Treatment Plant	Brooklyn, NY	2	$2,000,000
26th Ward Wastewater Treatment Plant	Brooklyn, NY	2	$2,000,000
Oakwood Beach Wastewater Treatment Plant	Staten Island, NY	1	$1,000,000

Hunts Point Wastewater Treatment Plant	Bronx, NY	3	$3,000,000

* Estimated cost of purchasing and installing the Fuel Cell Power Plants.

4.1 Yonkers Wastewater Treatment Plant

The Yonkers WWTP in Westchester County, New York was the world's first commercial fuel cell to consume ADG successfully. The fuel cell power plant was installed by the USEPA, NYPA, NYSERDA, EPRI, and the USDOE to assess and test "the technical viability of ADG as a fuel for fuel cells" (Spiegel 2003, 709). Prior to the implementation of this technology in Yonkers, WWTPs located in Japan attempted to utilize unmodified phosphoric acid fuel cells without success. Their unsuccessful attempts were due to the fact that ADG is a sulfurous, dirty gas which must be processed and cleaned before it can be properly utilized in a fuel cell which contains contaminant sensitive membranes and catalysts. The Yonkers WWTP demonstration project "addressed two major issues: development of an ADG cleanup system to remove fuel cell contaminants… from the gas and testing of a modified PC 25 model C fuel cell power plant operating on the cleaned, but dilute, ADG" (Spiegel 2003, 710). This will be further discussed in following sections.

The Yonkers WWTP is a publicly owned treatment works (POTW) operated by the Westchester County Department of Environmental Facilities. The plant treats sanitary and municipal wastes from an area approximately 69,000 acres. The plant processes between 95 million and 127.7 million gallons (when at full capacity) of wastewater and sludges per day. From the onsite anaerobic digestion treatment processes, an average of 17,000 standard cubic feet (scf) of ADG is produced daily (Kishinevsky 1997, 3-1). Typically, 65 to 70% of the ADG produced onsite is utilized in boilers and engines for onsite heat and energy needs. Before the installation of the fuel cell power plant, any unused ADG (about 5000 to 6000 scf) was flared (Kishinevsky 1997, 3-1). The installed fuel cell power plant currently utilizes half of this excess ADG (2500 to 3000 scf) and applies it towards power generation.

Installed in 1997, the Yonkers WWTP project received international attention for its innovative use of fuel cells. The project earned the 2000 Environmental Project of the Year Award from the Association of Energy Engineers. The project was implemented as a way to use “free gas” to create electricity, avoid flaring of ADG, and reduce emissions (NYPA New Technology Programs).

4.2 The Modified PC25 Model C Fuel Cell Power Plant

The equipment chosen for the ADG demonstration project at the Yonkers WWTP, and later installed at four other WWTPs in New York City, was the PC 25 model C fuel cell power plant manufactured by UTC Fuel Cells (a subdivision of UTC Power) located in South Windsor, Connecticut. This unit was partnered with a specifically engineered Gas Pretreatment Unit (GPU) designed for integration with the PC 25 C by US Filter (now owned by Siemens). The PC 25 model C fuel cell is a commercial, natural-gas-fueled 200 kW phosphoric acid fuel cell that was originally designed to utilize natural gas to generate electricity. As previously stated, this demonstration had to overcome major obstacles including removing contaminants from the ADG and utilizing a dilute methanous gas (approximately 60% methane) containing carbon dioxide in a power plant designed to consume natural gas (Spiegel 2003, 710). Table 4 lists the typical chemical composition of natural gas.

Table 4: Typical Composition of Natural Gas (Wikipedia.com)

Component*	wt. %
Methane (CH_4)	70 to 90
Ethane (C_2H_6)	5 to 15
Propane (C_3H_8) and Butane (C_4H_{10})	less than 5
CO_2, N_2, H_2S, water, and odorants	Trace

* Note: the actual concentrations of gaseous components in natural gas vary by the gas fields from which it was harvested.

The modified PC 25 model C fuel cell was installed in three main modules: the gas pretreatment unit (GPU) module, the PC 25 C fuel cell, and the cooling module. Figure C is a photograph taken of the complete ADG fuel cell power plant at the Yonkers site. Figure D is a schematic diagram of the ADG fuel cell power plant.

Figure C: Photograph of ADG Fuel Cell Power Plant (Spiegel 711)

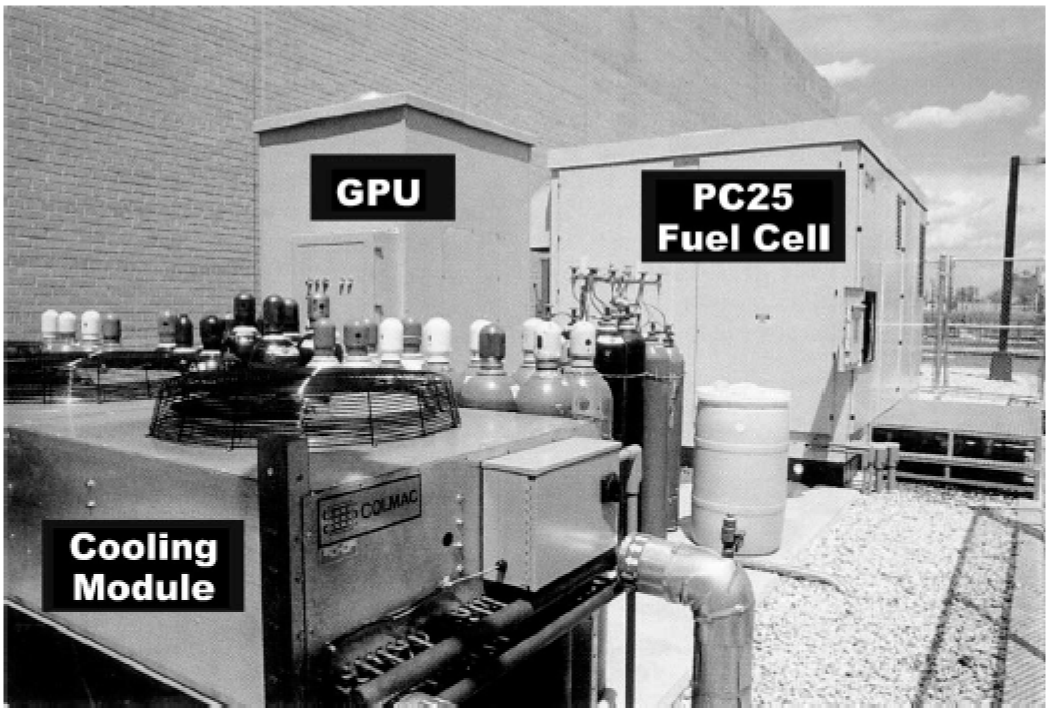
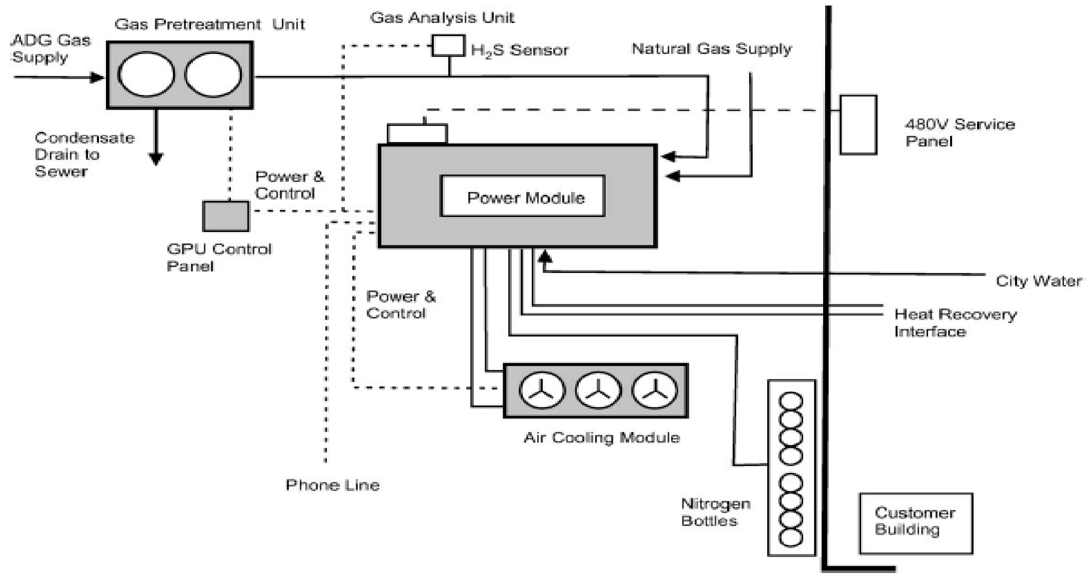


Figure D: Schematic Diagram of a Typical ADG Fuel Cell Power Plant Installation (Spiegel 711)



According to Homer Purcell, Vice President of Sales at UTC Power in South Windsor, Connecticut, for a 200 kW PC 25 C fuel cell power plant, the fuel cell system is designed to flow up to 4,800 ft^3 per hour. In order for a wastewater treatment plant to be considered for the installation of a PC 25 C fuel cell power plant, a nominal ADG flow of 3,600 ft^3 per hour is preferred with at least 60% methane content. Lower methane content (down to 50%) can be utilized at higher pressure and gas flow (Purcell).

4.2.1 The Gas Pretreatment Module

The gas pretreatment unit module consists of a coalescing filter, a blower motor, an oxygen injection system, and a desulfurizing unit containing two 1200 pound non-regenerable potassium hydroxide-impregnated carbon beds designed to remove hydrogen sulfide gas. The carbon beds are piped and valved in such a way to allow them to operate in series or parallel (Kishinevsky 1997, 3-1). This effectively allows the module to continue operating on a single bed while the other is changed out, dismissing the need to shut the power plant down for routine GPU maintenance. "To achieve a 40,000 – 50,000 h reformer catalyst life, the stated goal of the fuel cell manufacturer, requires that maximum concentrations of both sulfur and halide contaminants to be less than 3 ppmv in the pretreated ADG" (Spiegel 2003, 713). Table 5 lists the fuel contamination limits for proper operation of the PC 25 fuel cell power plant. Table 6 lists the ADG pretreatment requirements for use in the PC 25 fuel cell.

Table 5: ADG Fuel Contaminant Limits for Fuel Cell Applications (Spiegel 391, Spiegel 713)

ADG Contaminant	Fuel Cell Power Plant Requirements[a]	Concerns
Sulfur (H_2S)	< 3 ppmv[b]	Poison to fuel processor reforming catalyst
Halogens (F, Cl, Br)	< 3 ppmv[c]	Corrosion of fuel processor components
Non Methane Organic Carbons (NMOCs)	<0.5% Olefins (unsaturateds chemical compound with at least one Carbon to Carbon Bond)	Poison to fuel processor shift catalysts
Oxygen (O_2)	<4%[d]	Overtemperature of fuel processor beds due to excessive oxidation
	<0.5%[e]	
Ammonia (NH_3)	<1 ppmv	Fuel cell stack performance
Nitrogen (N_2)	<3.5%	Ammonia formation in reformer, fuel cell stack performance
Water (H_2O)	remove all	Damage to fuel control valves, transport of bacteria
Bacteria/Solids	remove all	Fowling of fuel processor piping and beds

[a] operating on ADG (nominal composition 60% Methane, and 40% Carbon Dioxide)
[b] with zinc oxide sulfur guard bed installed in fuel processor.
[c] with optional halogen guard bed installed in fuel processor.
[d] with peak shave option installed in fuel processor.
[e] without peak shave option installed in fuel processor.

Table 6: ADG Pretreatment Requirements (Spiegel 1999, 392, Spiegel 2003, 713)

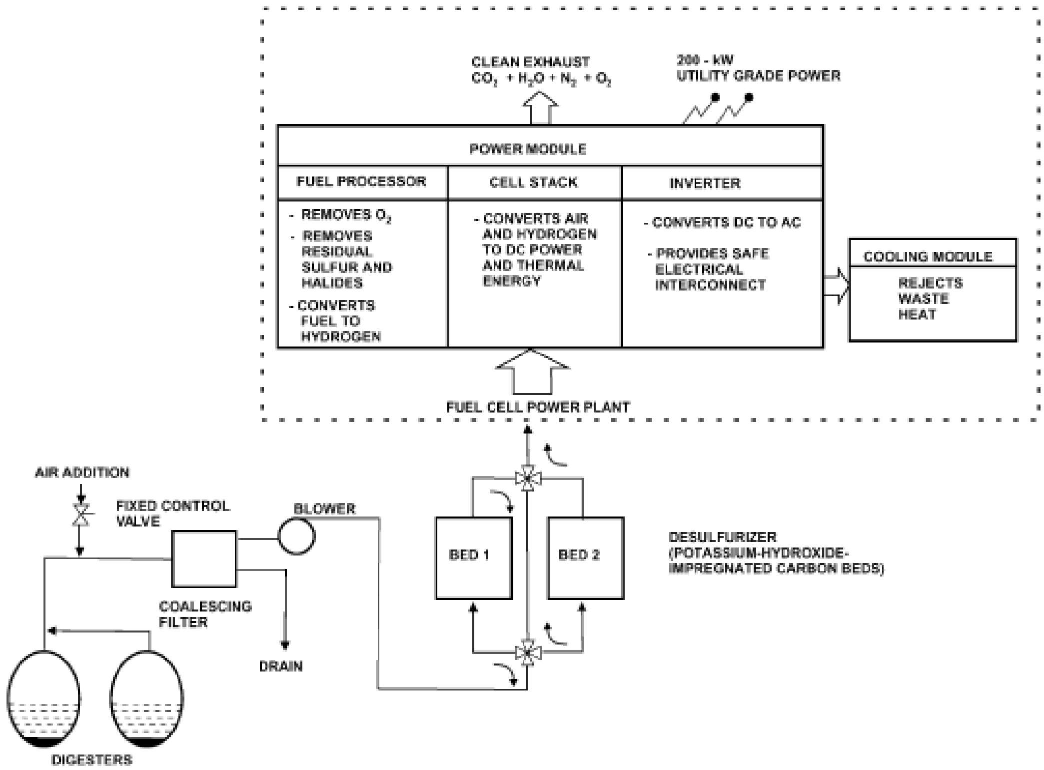
ADG Contaminant	Contaminant Concentration Range	Pretreatment requirements
Sulfur (H_2S)	up to 200 ppmv	Reduce sulfur content to <3 ppmv
Halogens (F, Cl, Br)	up to 4 ppmv	No pretreatment requirement, providing optional halogen guard is installed in the fuel processor
Non Methane Organic Carbons (NMOCs)	ppb to low ppm range	None
Oxygen (O_2)	<0.5%	None
	>0.5%	Requires peak shave option to be installed in the fuel processor
Ammonia (NH_3)	none	None

Nitrogen (N_2)	up to 4.0%	None
Water (H_2O)	saturated at 35-43 degrees celcius	Remove moisture from the gas stream, prevent further conensation in downstream piping
Bacteria/Solids	may be present in ADG	Provide for solids and moisture removal, prevent condensation, and keep ADG flowing

Hydrogen sulfide gas is effectively removed in the carbon beds through the Claus reaction, where hydrogen sulfide is chemically converted into water and elemental sulfur ($H_2S + ½ O_2 \rightarrow H_2O + S$) in the presence of potassium hydroxide (Spiegel 1999, 391). For the Claus reaction to successfully occur, a small amount of oxygen must be present. In order to control the amount of oxygen in the fuel beds, an air injection system was installed as part of the GPU to add oxygen (ideally to 0.3 to 0.5% volume) to the fuel mixture before entering the specialized carbon beds (Spiegel 1999, 391). The carbon beds are typically changed every six months (assuming ADG gas with less than 200 ppm H_2S), or when the pretreated ADG is detected leaving the carbon beds at greater than 3 ppmv. Specifically, the loading capacity of the carbon beds is 0.12 grams of sulfur per gram of activated carbon (Spiegel 2003, 713). When the carbon beds are changed out, the saturated carbon is disposed of at a Subtitle D landfill as a non-hazardous waste. Currently, the landfilling of approximately 2650 pounds of activated carbon and sulfur in fifty-five gallon drums would cost between $750 and $1000 (including transportation, disposal costs, and surcharges).

A blower unit pushes the ADG through the GPU and delivers it to the fuel cell power plant at the required pressure (0.089 kg/cm^2 to 0.14 kg/cm^2, depending on the methane content of the fuel) (Spiegel 2003, 713, 717). A coalescing filter is positioned upstream of the blower and the carbon bed to remove solids, liquids, and bacteria that may be present in the ADG leaving the digester (Spiegel 2003, 713). Figure E is a schematic of the GPU, fuel cell power plant and cooling module.

Figure E: Schematic Diagram of the GPU, Power Plant, and Cooling Module

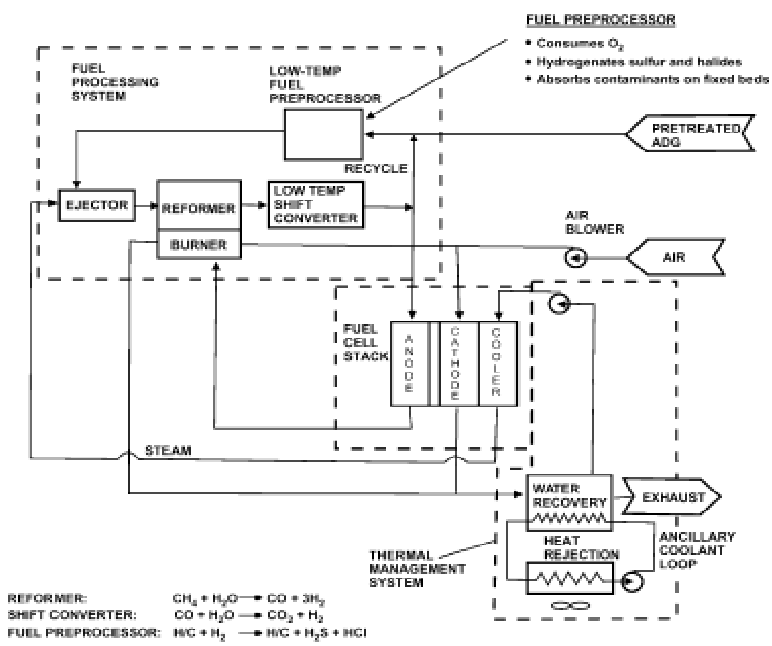


4.2.2 The PC 25 Model C Fuel Cell Power Plant and Cooling Module

Due to the varying ADG generation rates among wastewater treatment plants, and the varying electrical needs of facilities which may approve the use of a natural gas fired PC 25, UTC Power designed the PC 25 power plant to be installed as a modular unit with a capacity of 200 kW. For larger waste water treatment plants generating larger amounts of ADG, a megawatt size module may be considered for future applications (Spiegel 1999, 394). Per an interview with Homer Purcell, Vice President of UTC Power, currently no megawatt modular units have been installed at a WWTP in the United States to consume ADG. As can be seen in Figure E and Figure F, the PC 25 C fuel cell power plant is made up of three units: the fuel processing system, the fuel cell stack, and the thermal management system (cooling module).

In the fuel processing system, pretreated ADG is treated again in the low temperature fuel preprocessor to remove additional contaminants, and to convert ADG into hydrogen (H_2) and carbon dioxide (CO_2) gas. In the low temperature fuel preprocessor, oxygen is chemically reduced in a peak shave gas apparatus. Remaining hydrogen sulfide and halides are hydrogenated, utilizing a small amount of hydrogen gas from the shift converter, and absorbed on a fixed bed of activated carbon. Any residual non-methane organic compounds are also absorbed onto the carbon bed (Spiegel 2003, 712).

Figure F: Schematic of the PC 25 Model C Fuel Cell Power Plant (Spiegel 2003, 712)



In the reformer, methane and water (produced as a byproduct in the fuel cell) are chemically converted in the presence of a metal catalyst to carbon monoxide and hydrogen gas. In the low temperature shift converter, the carbon monoxide generated in the reformer is reacted with water in the presence of another metal catalyst to form carbon dioxide and hydrogen gas. Figure F is a schematic of the fuel cell power plant which outlines the chemical reactions that take place in the reformer and shift converter.

Because of the air-reactive nature of the catalysts in the reformer and the shift converter, nitrogen (an inert gas) is used to blanket the catalysts when methanous gases are not being reformed or shifted.

Within the fuel cell stack, hydrogen (part of the anode gas stream) is electrochemically combined with oxygen (part of the cathode gas stream, essentially air pumped into the fuel cell from the surrounding environment) in the presence of a liquid phosphoric acid electrolyte to produce DC electricity and byproduct water (Spiegel 1999, 395). The electrochemical reactions occurring in the phosphoric acid fuel cell are (Greenhouse Gas Technology Center 2004):

at the anode:
$2\ H_2 => 4\ H^+ + 4\ e-$

at the cathode:
$O_2 + 4\ H^+ + 4e- = > 2\ H_2O + heat$

with the overall cell reaction: $O_2 + 2H_2 = 2H_20$

The byproduct water from the fuel cell stack is captured and reused in the reformer. The heat produced from the cell stack is transferred to an external heat rejecter (cooling module), through use of heat distributing coils containing an ethylene glycol solution, where it can be utilized for processes at the facility or released to the ambient environment. The DC power generated from the fuel cell stack is converted in the electrical inverter to utility grade AC power (Spiegel 1999, 395).

The PC 25 C fuel cell power plant is interconnected in parallel to the local electrical grid (in the case of the Yonkers WWTP, the local grid was owned and operated by Con Edison). Interconnection is established when installing a fuel cell power plant to supplement the electrical needs of the WWTP and to provide electricity in the case of a fuel cell failure. In some cases, electricity may actually be sold back to the electrical grid through a net-metering agreement. According to Homer Purcell of UTC Power, an ADG fuel cell opportunity has not been discovered at a wastewater treatment plant where enough ADG has been produced to exceed the WWTPs electrical needs. To establish an interconnection agreement, the electrical grid required assurances of utility grade power quality, power factor, surge protection, grounding, and the facility's load profile for a full year. The load profile successfully demonstrated that the fuel cell electricity generation would not cause feedback of power to the electrical grid under any circumstances (Kishinevsky 1997, 4-8).

4.3.3 Modifications to the PC 25 Model C Fuel Cell Power Plant Installation to Operate Utilizing Anaerobic Digestion Gases

In order to operate on anaerobic digestion gas at the Yonkers wastewater treatment plant, the 200 kW PC 25 Model C Fuel Cell Power Plant needed to be modified. These modifications included alterations to the cell stack assembly, reformer, thermal management systems, piping, valves, and operational controls (Kishinevsky 2003). Some of these modifications were engineered before the installation of the fuel cell power plant while some adjustments were made as problems were discovered. ADG is different from natural gas in the following ways (excerpted from Kishinevsky 2003):

- ADG contains trace quantities of sulfur compounds, typically in the form of hydrogen sulfide and organic compounds, which contain chlorine. Both of these species can react with the catalysts in the reformer system, resulting in deactivation of the catalysts.
- ADG typically contains 60% methane, while natural gas contains methane in excess of 95%. This lower methane content of ADG results in a higher volumetric flow of gas, which can increase system pressure drops.

The differences between anaerobic digester gas and natural gas led to the following modifications and additions to the PC 25 Model C (excerpted from Kishinevsky 2003):

- An external gas processing unit (GPU) was added to remove the hydrogen sulfide contained in the ADG stream.
- A halide absorber was added internally to the PC 25 C to remove these

compounds (mostly chlorides).

- Mechanical components, such as piping and valves, in the reactive gas supply system were enlarged to accommodate the larger volume flow rates resulting from the use of diluted methane fuel. This modification helped reduce system pressure drops.
- An external gas compressor skid was added to raise the inlet pressure of the ADG to compensate in part for the increased pressure drops of the diluted fuel.
- Fuel-to-air ratios over the entire operating range were adjusted within the wider-than-usual boundaries to compensate for broader-than-anticipated methane concentration variations in ADG.
- Additional drains were installed in the facility fuel line to remove large amounts of entrained water periodically blocking ADG supply to the GPU.
- A blower was installed to compensate for lower-than-anticipated ADG pressure from the Yonkers WWTP.

Lessons learned from the Yonkers WWTP Demonstration project were as follows (excerpted from Spiegel 2003, 717):

- ADG is less reliable than natural gas; consequently, fuel cells should be designed for dual-fuel capability with the ability to switch to natural gas should problems arise.
- ADG is “wet”, and special care is required to trap and remove condensate in ADG lines.
- External pressurization to approximately 0.14 kg/cm^2 (2 psi) of the ADG is required to provide sufficient fuel for the 200 kW operation.
- The amount of sulfur in ADG can vary, so the hydrogen sulfide detection system for monitoring GPU performance must be reliable.
- Standardized and more streamlined grid parallel interconnection procedures would help facilitate the installation of more of these units. (Sliker 2007)

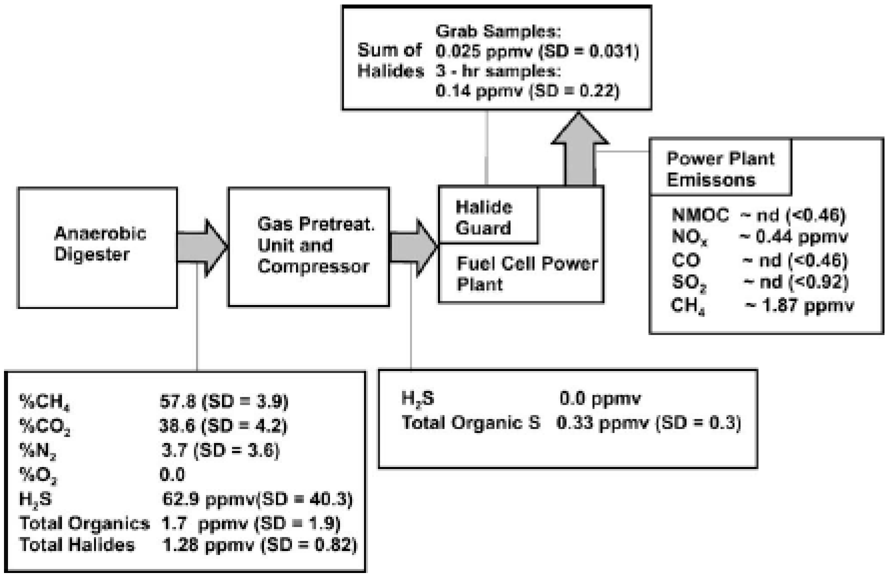
4.3.4 PC 25 C Fuel Cell Power Plant Emissions Reductions

At most wastewater treatment plants where anaerobic digestion is employed, ADG is combusted in boilers to heat anaerobic digester vessels (as previously mentioned, anaerobic digestion requires temperatures between 95 and 145 degrees Fahrenheit), consumed in internal combustion engines to generate electricity, or flared off (to reduce methane emissions and control odor). Less commonly, ADG is released uncombusted into the atmosphere. Often in warmer climates, byproduct heat is not as valuable and ADG is not utilized as efficiently (Kishinevsky 2003).

The byproducts of ADG combustion are carbon dioxide, water, nitrogen oxides, sulfur oxides, carbon monoxide, non methane organic compounds, and particulate (carbon). Additionally, due to incomplete combustion, a very small quantity of methane is often vented in exhaust from ADG combustion.

ADG is not combusted in a PC 25 C fuel cell power plant. As detailed in previous sections, ADG undergoes a series of purification treatments in the GPU and the fuel preprocessor before the methane content is chemically reformed to produce a nearly contaminant free mixture of carbon dioxide and hydrogen gas. The hydrogen gas is catalytically combined with oxygen to form water, electricity and heat. Field tests were conducted during the duration of the two year Yonkers demonstration project to measure the contaminant removal efficiency of the GPU, the preprocessor, and emissions from the cell stack. Figure G is a summary of the recorded ADG composition, contaminants, and fuel cell emissions (Spiegel 2003, 716). As the diagram shows, nearly 100% of the hydrogen sulfide removal occurs in the GPU. The data also shows that halides were removed at 89% efficiency (Spiegel 2003, 714).

Figure G: Summary of ADG Composition, Contaminants, and Fuel Cell Emissions (Spiegel 2003, 716)



The modified PC 25 model C fuel cell power plant reduces emissions by eliminating the need to flare ADG and by displacing utility-generated electricity. Several estimates of emissions reductions have been calculated. According to the Environmental Protection Agency's 2004 environmental technology verification report titled "Electric Power and Heat Generation Using UTC Fuel Cells' PC 25 C Power Plant and Anaerobic Digester Gas", a modified PC 25 C fuel cell power plant operating at 97% availability operating and a 72% Fuel Cell Capacity (166 kWh) effectively results in an estimated annual emission reduction of 1.82 tons of NO_x and 1426 tons of CO_2 (assuming utility generated electricity is generated at coal fired power plant) (Greenhouse Gas Technology Center 2004). Appendix B is an explanation of the equations involved with these estimations. The New York Power Authority estimates that an additional 20.4 tons of regulated emissions reduction, primarily SO_x, are accomplished per year operating at 97% availability (Kishinevsky 2003). An additional 0.3 to 0.4 tons per year of non-methane organic compounds emissions are eliminated (Kishinevsky 2003).

Due to the negligible amount of regulated emissions, PC 25 C fuel cell power plants are not regulated as stationary sources of air pollution under the Clean Air Act. Therefore, there is no Title V permit required to operate this fuel cell power plant (Staniunas).

4.4 New York Power Authority Sponsored Fuel Cell Projects

In August of 2000, the New York Power Authority installed ten natural gas powered General Electric Model LM 6000 simple-cycle turbine units in New York City to meet the growing energy needs of the city. As part of the project, the NYPA pledged to offset 100% of the emissions from the new turbines. Based partially on the success of the Yonkers WWTP demonstration project, this offset was accomplished through the installation of eight PC 25 C fuel cell power plants at four wastewater treatment plants in the New York City vicinity. These fuel cell power plants were installed at the Red Hook (2 Fuel Cells), 26th Ward (2 Fuel Cells), Oakwood Beach (1 Fuel Cell), and Hunts Point (3 Fuel Cells) wastewater treatment plants. Along with NYPA, financial and technical support was also provided by NYSERDA, the NYDEP, the United States DOE, and the US Department of Defense (Kishinevsky 2003).

Figure H: Pictures of Installed PC 25 C Fuel Cell Power Plants (courtesy of Kishinevsky 2003)

26th Ward WWTF – Brooklyn

Oakwood Beach WWTF – Staten Island


Red Hook WWTF


Hunts Point WWTF

4.4.1 Improvements Engineered into the PC 25 C Fuel Cell Power Plants

Based on lessons learned from the Yonkers demonstration project, several improvements were made to the PC 25 C fuel cell power plants that were installed at the four wastewater treatment facilities in New York City (Kishinevsky 2003):

- Dual fuel capability (operation on ADG or natural gas) was instituted to improve the availability of the fuel cell power plants.
- Smaller reformers, reformer burners, and cell stack gas manifolds were utilized to minimize fuel pressure drops.
- More phosphoric acid electrolyte was utilized in the fuel cells to accommodate the higher evaporation rate of the electrolyte due to the required higher ADG pressures and flow rates (compared to natural gas, which the PC 25 C was originally designed to consume).
- More rugged components, such as gas manifolds, were installed to accommodate the higher ADG pressure and to prolong the life-expectancy of system components.
- Plume suppression systems for the outdoor installations (26th Ward, Oakwood Beach, and Hunts Point) were installed to eliminate water vapor plumes.
- Ventilation systems for the indoor installation (Red Hook) were engineered

to evacuate gases vented from the fuel cell.

- Remote Automated Diagnostics and Data Acquisition (RADAR), a tool which is used to monitor the operation of the power plants, was installed and utilized at all of the locations. RADAR provides the ability to remotely retrieve power plant data over public telephone networks.
- A valve control was installed in each of the fuel cell units to automate (computer operate) fuel blending. Natural gas is blended with the ADG to supplement the fuel when low ADG pressures are detected.
- A natural gas pipeline was run directly to the reformer burner to assist in power plant start up.

4.4.2 Performance of the PC 25 C Fuel Cell Power Plants

Since their installation, the performance of the power plants have been recorded and monitored by NYPA and NYSERDA project managers. Specifically, the fuel cell availability, the fuel cell capacity, fuel consumption (both ADG and natural gas), and electricity generation are the parameters that are measured and analyzed. Table 7 is a summary of the recorded data as of the summer of 2006.

Table 7: Summary of Recorded Data for PC 25 C Fuel Cell Power Plants – System Startup to Summer of 2006 (NYSERDA 2006)

Unit	System Startup	Availability *	Average Capacity *	% ADG*	% Natural Gas*	Generation to date (kWh)
Red Hook Unit 9274	June 2003	82%	102 kW (51%)	3%	97%	2,446,200
Red Hook Unit 9275	June 2003	77%	98 kW (49%)	5%	95%	2,510,900
26th Ward Unit 9260	July 2003	95%	138 kW (69%)	76%	24%	3,622,300
26th Ward Unit 9263	July 2003	86%	120 kW (60%)	68%	32%	3,133,700
Oakwood Beach Unit	August 2003	95%	120 kW (60%)	61%	39%	2,735,300

9277						
Hunts Point Unit 9276	January 2005	97%	143 kW (71.5%)	91%	9%	2,419,000
Hunts Point Unit 9278	January 2005	93%	144 kW (72%)	95%	5%	2,435,700
Hunts Point Unit 9279	January 2005	90%	134 kW (67%)	83%	17%	2,250,200
Total		89%	126 kW (63%)	70%	30%	21,553,300

* Availability Factor = lifetime percentage of time unit available to produce power
* Capacity Factor = lifetime average output during unit availability
* % ADG = ADG percentage of total fuel use
* % NG = Natural gas percentage of total fuel use

As can be seen from Table 7, the average availability of the fuel cell power plants over the given period was 89%, while the average fuel cell capacity was 126 kW, or 63%. This was due primarily to the low availability of ADG fuel at the sites (NYSERDA 2006). In order for the PC 25 C to effectively operate at full capacity, a minimum of 2000 to 2300 ft^3 per hour of methane must be supplied to the unit through ADG supply or natural gas (Purcell 2007). When ADG supply is low or unavailable, natural gas can be blended in and consumed in conjunction with the ADG in the fuel cells. Natural gas can also be blended with ADG to increase the methane content of the fuel mixture. On occasions when natural gas was the primary fuel being used in the fuel cells, the NYPA reduced the capacity of the fuel cells to 100 kW due to the high price of natural gas (NYSERDA 2006).

Equipment and infrastructure malfunctions, as well as maintenance operations, led to availability issues at several of the waste water treatment plants. According to the final report issued by NYSERDA to NYPA under a cofunding agreement, “1.6 MW Fuel Cell Distributed Generation Project Utilizing Renewable Anaerobic Digester Gas”, most of the ADG supply shortages and pressure irregularities are due to poor maintenance of the ADG supply distribution pipelines and pressure regulators at the various wastewater treatment plants. At many of the project locations, ADG fuel shortages were severe. For example, at the Red Hook WWTP, ADG was not available for several months due to operational problems at the facility (NYSERDA 2006). At Hunts Point, a malfunction of the ADG supply distribution system lead to a one year delay of the system startup (NYSERDA 2006). At most locations, there were periods of time where the quality or available pressure of the ADG was insufficient for fuel cell operation (NYSERDA 2006). Before installation of the automated valve controls, natural gas and ADG were blended manually through remote or on site adjustments when poor quality or supply of ADG deemed it necessary. This caused interruptions in fuel cell operation. Afterwards, these automated controls effectively increased the availability of the fuel cell power plant units (Sliker 2007). There have been no major malfunctions with the GPU, the modified PC 25 C fuel cell power plant, or cooling modules as of the date of this thesis (Sliker 2007).

5.0 Methodology

The conclusions of this research will be verified through the triangulation of information obtained through in-depth interviews and extensive literature research (see Section 3). For the purpose of this thesis, a literature review has been prepared. During this search, university databases and libraries (Rochester Institute of Technology and Yale University) were scanned for pertinent articles, books, and case studies. Scholarly articles were then obtained through focused internet searches using various search engines, such as Google and Yahoo. Publications from state, local, federal, and international governments and organizations were considered for review. Many project documents (some that were confidential prior to this thesis) were discovered and obtained through interviews. In addition, literature from Non-Government Organizations (NGOs), International Voluntary Initiative Organizations, academics, and professionals in the hydrogen development field were included in the literature summary. Due to the fact that fuel cells are highly technical devices currently in the stages of engineering, development, and improvement, some requested documents and information were proprietary and not attainable.

Government and non-government databases were utilized to collect vital statistics for this thesis.

Focused, in-depth interviews were conducted to obtain new information and perspectives. Included in the interview process were representatives of state and federal agencies, engineers, scientists, and salesmen from private industry, and private consultants. Case studies were utilized as a significant source of information. Qualitative and quantitative interviews were conducted to elicit depth and detail on the research topic. Quantitative questions were presented to appropriate interviewees. Each interview was unique, while using a set guideline of questions (see Appendix A). The list of questions were adjusted and expanded upon during the interview processes (each progressive interview) to focus on the expertise of the interviewee and the evolution of the topic being studied. The primarily focus of the interviews were on meanings and frameworks of the thesis topic.

Through interview, additional topics of interest were uncovered and are addressed in this final report.

A majority of the interviews were conducted as recorded phone conversations. Some were not recorded due to the preference of the interviewee. All interviewees agreed to have their names included, and any information they relayed during the interview, included in this final report.

Case studies are included as part of the thesis to provide support for the conclusions and demonstrate the potential of this new technology. Interviews were conducted with the researchers and coordinators of new and innovative hydrogen energy projects that have been carried out.

There were costs associated with this thesis. Most of the expenses were encountered due to research and interviewing. The following is a brief outline of the financial expenditures:

- Travel expenses: vehicle depreciation, vehicle maintenance, fuel, airfare, and tolls.
- Communications: primarily phone calls (both short and long distance).
- Supplies: digital recorder (to record interviews), the media for the recorder, and office supplies.
- Research tools: fees for articles, purchasing of books, electricity to power research equipment.
- Vacation and personal days away from work.

Research associated with this thesis has been considered complete due to the fact that all case study locations have been evaluated, all interviews have been conducted, and any additional information gathered is repetitive.

6.0 Results

6.1 Economic Assessment of Installing and Utilizing PC 25 C Fuel Cell Power Plants at Wastewater Treatment Plants Operating on Anaerobic Digestion Gases

A majority of the statistics utilized in this economic assessment were obtained from project documents, interviews, and government and non government databases. Additional statistics collected during the Yonkers demonstration project and the four emissions offset projects in New York City were also utilized. Key assumptions included in this economic assessment are described in the following paragraphs. The following figures are current cost estimates, as of the Fall of 2007.

6.1.1 Estimated Costs and Assumptions

The PC 25 C fuel cell power plant is engineered by UTC Power to have an effective life span of 20 years (Kishinevsky 2003). The maximum electricity generation potential of the unit is 200 kW per hour. At full capacity, 900,000 BTU of byproduct heat is produced. The fuel cell power plants are designed to function 24 hours per day, 365 days per year. This converts to a maximum operation potential of 8760 hours per year.

The fuel cell stack must be replaced every five to seven years. The cost for this cell stack replacement ranges from $200,000 to $300,000 (Trocciola 2007). For the purpose of this cost assessment, the average cost of this replacement will be $250,000 every seven years. It will be assumed that this replacement will be undertaken two times during the 20 year effective life span of the PC 25 C fuel cell power plant.

In Ron Spiegel's 1999 report titled, "Fuel Cell Operation on Anaerobic Digester Gas: Conceptual Design and Assessment", which was written to support the demonstration project at the Yonkers WWTP, an 80% fuel cell capacity factor was predicted by the authors for a preliminary economic assessment (396). However, based on fuel cell performance information from the 2006 NYSERDA Report, "1.6 MW Fuel Cell

Distributed Generation Project Utilizing Renewable Anaerobic Digester Gas", the actual capacity factor was found to be substantially lower than this. Actual data collected from the eight fuel cell power plants installed at the four NYPA emissions offset projects demonstrate an average fuel cell capacity of 63% (see table 7). This figure will be utilized in this economic assessment. Additionally, the fuel cell power plants were available 89% of the time (NYSERDA 2006).

PC 25 C retail costs and installation costs were obtained through multiple Fall 2007 interviews with Homer Purcell of UTC Power, Bob Tierney of UTC Power, John Trocciola (retired UTC Power), and Ron Spiegel of the US EPA. The retail cost of the PC 25 C fuel cell power plant currently ranges from \$3000 to \$4000 per kWh of capacity. The installation cost for these units ranges from \$1000 to \$2000 per kW of capacity. For the purpose of this economic assessment, the average PC 25 C retail cost and installation cost, \$3500 and \$1500 per kW of capacity, respectively, will be used. The combined retail and installation cost of the Gas Pretreatment Unit is \$100 to \$200 per kW. The average GPU cost of \$150 per kW will be utilized in this evaluation.

According to Guy Sliker of the NYPA, the average combined operating and maintenance (O&M) cost for the GPU, fuel cell power plant, and the cooling module is \$0.020 and \$0.025 per kWh of operation. The average O&M cost of \$0.0225 per kWh of operation will be used for this cost estimate. This cost accounts for the service contract between NYPA and UTC Power, and the waste disposal costs associated with changing the activated carbon beds in the GPU. More specific details about spent carbon disposal can be found in Section 4.2.1. The cell stack replacement is not accounted for as part of this maintenance cost. Also, large repairs or physical adjustments are not included.

Federal and state level incentives are available to encourage renewable energy projects. Additionally, Non Government Organizations (NGOs) advocating renewable energy projects offer incentives in several states and regions. These incentives are in the form of tax credit incentives, grants, loans, and bonds. Appendices F, G, H, I, and J are tables of the available incentives at the federal and state level (including NGOs). Federal, state, and private funding were received for the completion of the Yonkers demonstration project and the four emissions offset projects.

John Trocciola, formerly of UTC Power and currently a private consultant, has been involved with the installation of multiple ADG fuel cell power plants at wastewater treatment plants, landfills, and farms across the United States and in other countries. In his experience, he feels the only guaranteed support for these projects has come in the form of Federal tax credits (Trocciola 2007). Many of the federal, state, and NGO incentives are offered from appropriated funds each year and very competitive (Trocciola 2007). Currently the United States Internal Revenue Service will allow a $500 tax credit per 0.5 kW of operational capacity credit for renewable energy project costs (see Appendix I) up to 30% of the project cost to corporations and utilities (DSIRE 2007). For the purpose of this study, a federal tax credit of $500 per 0.5 kW of operational capacity up to 30% of the project cost will be included in this economic assessment.

Average electricity costs and natural gas costs in the United States were obtained through the Department of Energy's Energy Information Administration (www.eia.doe.gov). As of July 2007, the average electricity and natural gas costs to a large industrial customer are, respectively, $0.0675 per kilowatt-hour and $7.48 per MMBTU (million British thermal units) of natural gas. See Appendices D and E for average electricity and natural gas costs in the United States and an explanation of converting kcf to MMBTU. A standard 10% carrying charge will be added to the natural gas cost throughout the cost assessment.

Other assumptions that should be considered are as follows:

- This quantitative cost assessment analysis does not include the value of intangibles, or less tangible benefits such as improved public image, environmental benefits from reduced emissions, or reliable energy benefits. These benefits will be discussed qualitatively later in this report.

- End of life span costs, such as disassembly and disposal of the fuel cell components were not included in this analysis. Because this is such a new technology, no data regarding these costs are available. Additionally, it is anticipated that the modular system will be removed and replaced after 20 years of service, and the company installing the new units will recycle the materials and reuse components from the old unit (Spiegel 2007).
- Back up power capabilities and willingness-to-pay to avoid loss of service were not included in this cost assessment. In the case studies that have been studied, and through information gathered during interviews, the power generated by the installed PC 25 C fuel cell power plants are a very small fraction of the total energy consumed at the facility and currently do not represent a viable backup power system.
- The small financial savings, in the form of saved yearly tax payments, for the reduced NO_x and SO_x emissions from the facility have not been included in this assessment.
- It was discovered that, due to electric utility deregulation, public utilities may receive discounted electricity costs. For the purposes of this study, the electricity costs for large industrial customers will be used.

For the purpose of this point estimate cost assessment, a 10% discount rate was used to calculate the net present value (NPV) of installing and utilizing a PC 25 C fuel cell power plant over the 20 year effective life span. This high discount rate was chosen based on the volatile nature of electricity and natural gas prices and the variability in production of ADG at the wastewater treatment plants.

Two point estimate cost assessments will be demonstrated. The point estimates that will be utilized are the average costs per parameter. For the first assessment, it will be assumed that only the electricity generated by the fuel cell power plants is utilized onsite. The second assessment will include the use of both the heat and the electricity generated. For the second assessment, the heating equivalency of the natural gas at an 85% thermal efficiency will be utilized to determine the value of the heat generated by the fuel cell power plant (Spiegel 1999). Sensitivity analysis will be performed for several variables to explore one and two dimensional effects that single or multiple variables will have on the net present value of each scenario.

Climate variations lead to different heat demands. For example, a wastewater treatment facility in the Northeast United States will require more heat during operation, than a facility in the Southwest United States. Also, there are seasonal variations in heat demand. During the colder seasons of the year, heat demand is greater than in warmer seasons. In Spiegel's 1997 report, "Fuel Cell Operation on Anaerobic Digester Gas: Conceptual Design and Assessment", the author estimated that in a Northern US climate there is a demand for 62% of the heat generated from the fuel cell in the winter months, and a 23 % demand in the summer months (397). In some southern climates, no heat is needed at all. This thermal variation is one of the motivating factors behind performing the two assessments.

Table 8 is a summary of the variables that will be used in the following cost assessments (summarized from Section 6.1.1).

Table 8: Summary of ADG PC 25 C Fuel Cell Power Plant Variables

FC Electricity Output (kW)	FC Heat Output (BTU)	Thermal Efficiency (%)	FC Capacity Factor (%)	FC Availability (%)	FC Cost ($/kW)
200	900000	85	63	89	3500

FC Installation Cost ($/kW)	GPU Cost ($/kW)	Incentives/Grants ($/kW)	Operating & Maintenance Cost (O&M) ($/kWh)	Large Maintenance Projects ($)	Frequency of large maintenance project (yrs)
1250	150	1000	0.0225	250000	7

Effective Life of Equipment (yrs)	Cost of Electricity ($/kWh)	Cost of Natural Gas ($/MMBTU)	10% Carrying Charge for Natural Gas	Days of Operation Per Year	Discount Rate (%)
20	0.0675	7.48	0.748	365	10

6.1.2 Quantitative Point Estimate Cost Assessment – Utilization of Electricity Only

The following series of equations were used to calculate the yearly net cash flow from utilizing the electricity only from the modified PC 25 C fuel cell power plants at wastewater treatment plants. A spreadsheet summary of all calculations is provided as Appendix K.

Initial Cost = FC Electricity Output (FC Cost + FC Installation Cost + GPU Cost - Incentives/Grants)

Yearly Electricity Generation = FC Energy Output x Hours of Operation per Day x Days of Operation per Year x FC Capacity Factor x FC Availability

Yearly Electricity Savings = Yearly Electricity Generation x Cost of Electricity

Yearly O&M Costs = Yearly Electricity Generation x Operating and Maintenance Costs

Net Cash Flow per Year (Electricity Only) = Yearly Electricity Savings - Yearly O&M Costs

Using the above formulas with the given variables in Table 8, a net cash flow of $44,205 per year was estimated. The initial project cost, the yearly electricity savings, and the yearly O&M costs are $780,000, $66,308.32, and $22,102.79 respectively.

To determine the net present value (the sum of the discounted present values of each year's net cash flow at a 10% discount rate minus the initial expenditure) of installing and utilizing a PC 25 C fuel cell power plant over the 20 year effective life span, the following equation was used:

$$NPV = \sum_{t=1}^{T} C_t/(1+r)^t - C_0$$

Where:

NPV = net present value

t = discount period (in this case, years)

r = discount rate

C_t = net cash flow in year t

C_0 = net cash flow in year 0, or initial cash flow (project cost)

The net present value (only taking into account the generated electricity), given the stated variables in table 8 and utilizing a discount rate of 10% over the 20 year life span of the fuel cell power plant is calculated to be -$597,775.25. The internal rate of return (the annualized effective compounded return rate which can be earned on the invested capital) of this project, calculated using Microsoft Excel, is -6%. Table 9 is a summary of this calculation of the net present value demonstrating the discounted cash flow for years 1 through 20. Due to the large expenditures for stack replacements at years 7 and 14, a payback period could not be calculated.

Table 9: Net Present Value of Using Only the Electricity Generated from the PC 25 C Fuel Cell Power Plant at a Wastewater Treatment Plant

Time Period (T) year	Net Cash Flows (CF)*	Discount Rate	Discounted Cash Flow
1	44,205.59	10%	40,186.90
2	44,205.59	10%	36,533.54
3	44,205.59	10%	33,212.31
4	44,205.59	10%	30,193.01
5	44,205.59	10%	27,448.19
6	44,205.59	10%	24,952.90
7	(205,794.41)	10%	(105,605.07)
8	44,205.59	10%	20,622.23
9	44,205.59	10%	18,747.48
10	44,205.59	10%	17,043.17
11	44,205.59	10%	15,493.79

12	44,205.59	10%	14,085.26
13	44,205.59	10%	12,804.78
14	(205,794.41)	10%	(54,192.10)
15	44,205.59	10%	10,582.47
16	44,205.59	10%	9,620.42
17	44,205.59	10%	8,745.84
18	44,205.59	10%	7,950.76
19	44,205.59	10%	7,227.97
20	44,205.59	10%	6,570.88
		Gross Present Value (GPV)	**182,224.75**
*** Cell stack replacements occurred at years 7 and 14**		**Initial Investment**	**780,000.00**
		Net Present Value (NPV)	**(597,775.25)**
		Internal Rate of Return after 20 years	**-6%**

6.1.3 Quantitative Point Estimate Cost Assessment – Utilization of both Electricity and Heat

A series of equations were employed to calculate the yearly net cash flow from utilizing the heat from the modified PC 25 C fuel cell power plants at wastewater treatment plants. A spreadsheet summary of all calculations is provided as Appendix K.

Yearly Heat Generation = FC Heat Output x Hours of Operation per Day x Days of Operation per Year x Capacity Factor x Availability x Thermal Efficiency

Yearly Savings from Heat Generated = Yearly Heat Generation x (Cost of Natural Gas + Natural Gas Carrying Charge)

Net Cash Flow per Year (Both Electricity and Heat) = Yearly Electricity Savings + Yearly Savings from Heat Generated - Yearly O&M Costs

Using the above formulas with the variables in table 8, along with the yearly electricity savings from Section 6.1.2, a net cash flow of $75,122.09 per year was estimated. The initial project cost, the yearly electricity savings, the yearly savings from heat generated, and the yearly O&M costs are $780,000, $66,308.32, $30,916.50, and $22,102.79 respectively.

The calculated net present value (utilizing both the electricity and heat onsite), given the stated variables in Table 8 and utilizing a discount rate of 10% over the 20 year life span of the fuel cell power plant, is calculated to be -$334,565.62. The internal rate of return of this project, calculated using Microsoft Excel, is 3%. Table 10 is a summary of the calculation of the net present value demonstrating the discounted cash flow for years 1 through 20. Due to the large expenditures for stack replacements at years 7 and 14, a payback period could not be calculated.

Table 10: Net Present Value of Using Both the Electricity and Heat Generated from the PC 25 C Fuel Cell Power Plant at a Wastewater Treatment Plant

Time Period (T) year	Net Cash Flows (CF)	Annual Discount Rate	Discounted Cash Flow
1	$75,122	10%	68,292.81
2	$75,122	10%	62,084.37
3	$75,122	10%	56,440.34
4	$75,122	10%	51,309.40
5	$75,122	10%	46,644.91
6	$75,122	10%	42,404.46
7	($174,878)	10%	(89,740.02)
8	$75,122	10%	35,045.01
9	$75,122	10%	31,859.10
10	$75,122	10%	28,962.82
11	$75,122	10%	26,329.84
12	$75,122	10%	23,936.21
13	$75,122	10%	21,760.19
14	($174,878)	10%	(46,050.82)
15	$75,122	10%	17,983.63
16	$75,122	10%	16,348.76
17	$75,122	10%	14,862.51
18	$75,122	10%	13,511.37
19	$75,122	10%	12,283.06
20	$75,122	10%	11,166.42
		Gross Present Value (GPV)	**445,434.38**
		Initial Investment	**780,000.00**
*** Cell stack replacements occurred at years 7 and 14**		**Net Present Value (NPV)**	**(334,565.62)**
		Internal Rate of Return after 20 years	**3%**

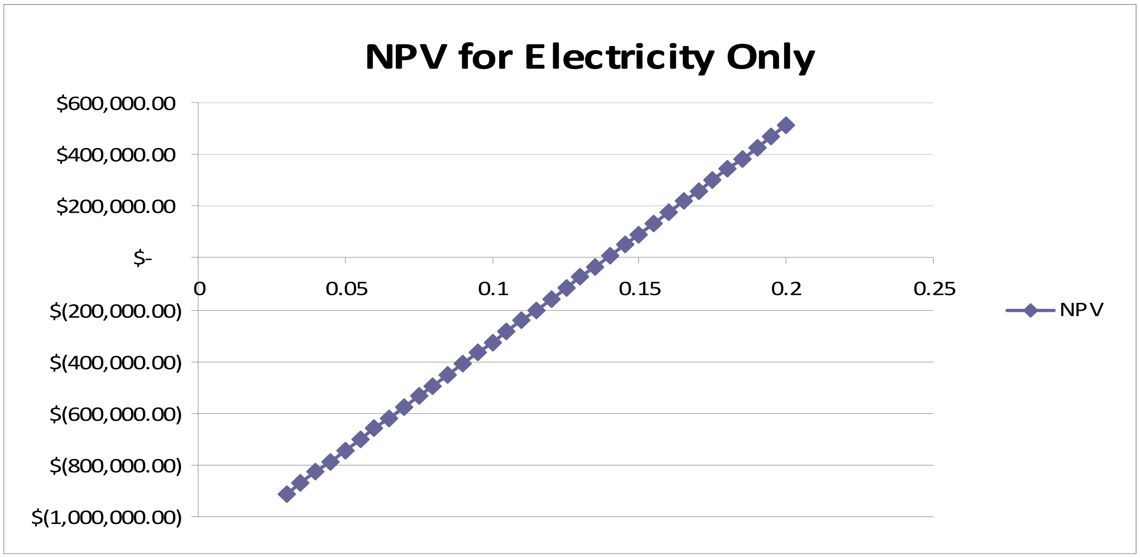
6.1.4 Sensitivity Analysis

Sensitivity analysis was performed to explore the effects on the net present value of changing variables of high importance in Table 8. Variables of high importance include the cost of electricity, fuel cell cost, the discount rate, incentives and grants, and the cost of natural gas. One dimensional sensitivity analyses were utilized to examine the effect of changing a single variable. Two dimensional sensitivity analyses were performed to explore the inter-relationship of two independent variables and the combined effect on the net present value of changing both variables. The following tables, graphs, and paragraphs are a summary of the analysis performed.

Table 11: One-Dimensional Sensitivity Analysis – Cost of Electricity and Net Present Values (Negative NPVs are shaded)

	Electricity Only	Electricity and Heat
Cost of Electicity ($/kWhr)	**$(597,775.25)**	**$ (334,565.62)**
0.08	$(493,234.39)	$ (230,024.77)
0.085	$(451,418.05)	$ (188,208.42)
0.09	$(409,601.71)	$ (146,392.08)
0.095	$(367,785.36)	$ (104,575.74)
0.1	$(325,969.02)	$ (62,759.39)
0.105	$(284,152.68)	$ (20,943.05)
0.11	$(242,336.33)	$ 20,873.29
0.115	$(200,519.99)	$ 62,689.64
0.12	$(158,703.65)	$ 104,505.98
0.125	$(116,887.30)	$ 146,322.32
0.13	$ (75,070.96)	$ 188,138.67
0.135	$ (33,254.62)	$ 229,955.01
0.14	$ 8,561.73	$ 271,771.35
0.145	$ 50,378.07	$ 313,587.70
0.15	$ 92,194.41	$ 355,404.04
0.155	$ 134,010.76	$ 397,220.38
0.16	$ 175,827.10	$ 439,036.73
0.165	$ 217,643.44	$ 480,853.07
0.17	$ 259,459.79	$ 522,669.41
0.175	$ 301,276.13	$ 564,485.76
0.18	$ 343,092.47	$ 606,302.10

Figure I: Graphical Representation: One-Dimensional Sensitivity Analysis – Cost of Electricity and Net Present Values



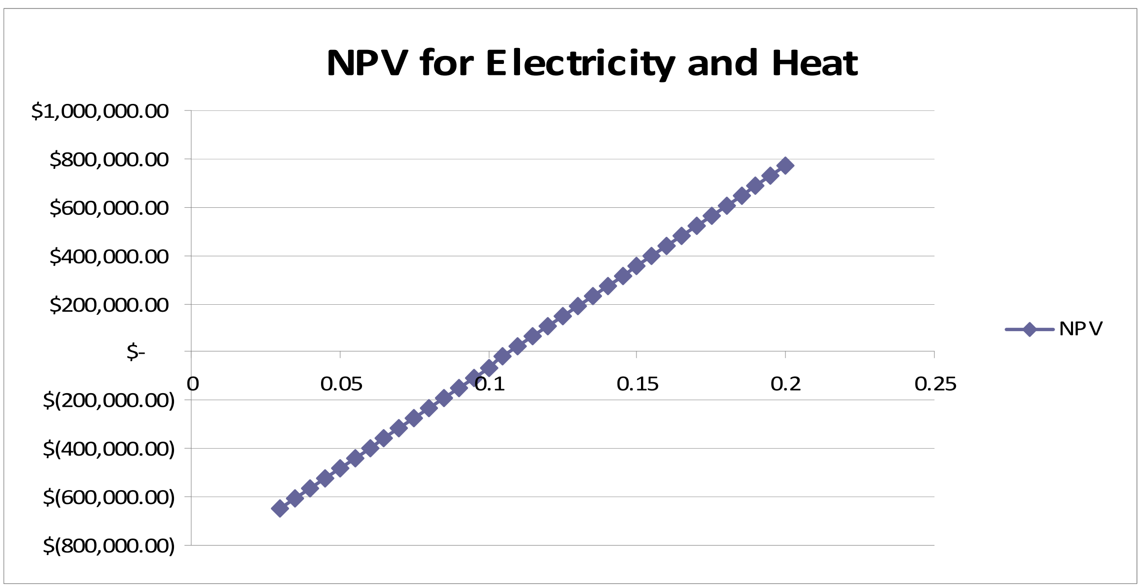


Table 12: One-Dimensional Sensitivity Analysis – Discount Rate and Net Present Values (Negative NPVs are shaded)

	Electricity Only	Electricity and Heat
Cost of Electicity ($/kWhr)	**$ (597,775.25)**	**$ (334,565.62)**
0%	$ (395,888.24)	$ 222,441.84
2%	$ (464,284.08)	$ 41,245.08
4%	$ (513,579.86)	$ (93,414.48)
6%	$ (549,804.91)	$ (195,195.04)
8%	$ (576,970.88)	$ (273,428.09)
10%	$ (597,775.25)	$ (334,565.62)
12%	$ (614,051.11)	$ (383,122.02)
14%	$ (627,057.45)	$ (422,293.40)
16%	$ (637,668.32)	$ (454,369.28)
18%	$ (646,497.18)	$ (481,008.97)
20%	$ (653,979.42)	$ (503,429.04)
22%	$ (660,427.53)	$ (522,531.70)
24%	$ (666,068.47)	$ (538,993.70)
26%	$ (671,068.99)	$ (553,328.33)
28%	$ (675,553.14)	$ (565,929.25)
30%	$ (679,614.36)	$ (577,101.60)

Table 13: One-Dimensional Sensitivity Analysis –Fuel Cell Cost and Net Present Values (Negative NPVs are shaded)

	Electricity Only	Electricity and Heat
Fuel Cell Cost ($/kW)	**$ (597,775.25)**	**$ (334,565.62)**
2000	$ (297,775.25)	$ (34,565.62)
2500	$ (397,775.25)	$ (134,565.62)
3000	$ (497,775.25)	$ (234,565.62)
3500	$ (597,775.25)	$ (334,565.62)
4000	$ (697,775.25)	$ (434,565.62)
4500	$ (797,775.25)	$ (534,565.62)
5000	$ (897,775.25)	$ (634,565.62)

Table 14: One-Dimensional Sensitivity Analysis – Incentives and Grants and Net Present Values (Negative NPVs are shaded)

	Electricity Only	Electricity and Heat
Incentives and Grants ($/kW)	**$ (597,775.25)**	**$ (334,565.62)**
0	$ (797,775.25)	$ (534,565.62)
500	$ (697,775.25)	$ (434,565.62)
1000	$ (597,775.25)	$ (334,565.62)
1500	$ (497,775.25)	$ (234,565.62)
2000	$ (397,775.25)	$ (134,565.62)
2500	$ (297,775.25)	$ (34,565.62)
3000	$ (197,775.25)	$ 65,434.38

Table 15: One-Dimensional Sensitivity Analysis – Cost pf Natural Gas and Net Present Values (Negative NPVs are shaded)

	Electricity Only	Electricity and Heat
Cost of Gas $/MMBTU	**$(597,775.25)**	**$ (334,565.62)**
2	$ (597,775.25)	$ (527,398.35)
2.5	$ (597,775.25)	$ (509,804.12)
3	$ (597,775.25)	$ (492,209.89)
3.5	$ (597,775.25)	$ (474,615.67)
4	$ (597,775.25)	$ (457,021.44)
4.5	$ (597,775.25)	$ (439,427.21)
5	$ (597,775.25)	$ (421,832.99)
5.5	$ (597,775.25)	$ (404,238.76)
6	$ (597,775.25)	$ (386,644.54)
6.5	$ (597,775.25)	$ (369,050.31)
7	$ (597,775.25)	$ (351,456.08)
7.5	$ (597,775.25)	$ (333,861.86)
8	$ (597,775.25)	$ (316,267.63)
8.5	$ (597,775.25)	$ (298,673.40)
9	$ (597,775.25)	$ (281,079.18)
9.5	$ (597,775.25)	$ (263,484.95)
10	$ (597,775.25)	$ (245,890.72)
10.5	$ (597,775.25)	$ (228,296.50)
11	$ (597,775.25)	$ (210,702.27)
11.5	$ (597,775.25)	$ (193,108.04)
12	$ (597,775.25)	$ (175,513.82)
12.5	$ (597,775.25)	$ (157,919.59)
13	$ (597,775.25)	$ (140,325.36)
13.5	$ (597,775.25)	$ (122,731.14)

Table 16: Two-Dimensional Sensitivity Analysis – Discount Rate, Electricity Cost and Net Present Values – Electricity Only (Negative NPVs are shaded)

	Cost of Electricity ($/kWhr)				
	$ (597,775.25)	0.08	0.085	0.09	0.095
Discount Rate (%)	0%	$ (150,301.64)	$ (52,067.00)	$ 46,167.64	$ 144,402.28
	2%	$ (263,499.43)	$ (183,185.57)	$ (102,871.71)	$ (22,557.85)
	4%	$ (346,699.75)	$ (279,947.71)	$ (213,195.67)	$ (146,443.63)
	6%	$ (408,961.96)	$ (352,624.78)	$ (296,287.60)	$ (239,950.42)
	8%	$ (456,410.61)	$ (408,186.50)	$ (359,962.39)	$ (311,738.28)
	10%	$ (493,234.39)	$ (451,418.05)	$ (409,601.71)	$ (367,785.36)
	12%	$ (522,331.35)	$ (485,643.44)	$ (448,955.54)	$ (412,267.63)
	14%	$ (545,729.84)	$ (513,198.80)	$ (480,667.76)	$ (448,136.72)
	16%	$ (564,866.12)	$ (535,745.25)	$ (506,624.37)	$ (477,503.49)
	18%	$ (580,769.04)	$ (554,477.79)	$ (528,186.53)	$ (501,895.27)
	20%	$ (594,184.24)	$ (570,266.17)	$ (546,348.10)	$ (522,430.03)
	22%	$ (605,658.45)	$ (583,750.82)	$ (561,843.19)	$ (539,935.56)
	24%	$ (615,597.27)	$ (595,408.79)	$ (575,220.31)	$ (555,031.83)
	26%	$ (624,305.09)	$ (605,599.53)	$ (586,893.96)	$ (568,188.40)
	28%	$ (632,013.04)	$ (614,596.99)	$ (597,180.95)	$ (579,764.91)
	30%	$ (638,898.63)	$ (622,612.34)	$ (606,326.05)	$ (590,039.75)

	Cost of Electricity ($/kWhr)				
	$ (597,775.25)	0.1	0.105	0.11	0.115
Discount Rate (%)	0%	$ 242,636.92	$ 340,871.56	$ 439,106.20	$ 537,340.84
	2%	$ 57,756.00	$ 138,069.86	$ 218,383.72	$ 298,697.58
	4%	$ (79,691.59)	$ (12,939.55)	$ 53,812.49	$ 120,564.53
	6%	$ (183,613.24)	$ (127,276.06)	$ (70,938.89)	$ (14,601.71)
	8%	$ (263,514.17)	$ (215,290.06)	$ (167,065.96)	$ (118,841.85)
	10%	$ (325,969.02)	$ (284,152.68)	$ (242,336.33)	$ (200,519.99)
	12%	$ (375,579.73)	$ (338,891.82)	$ (302,203.91)	$ (265,516.01)
	14%	$ (415,605.67)	$ (383,074.63)	$ (350,543.59)	$ (318,012.55)
	16%	$ (448,382.61)	$ (419,261.74)	$ (390,140.86)	$ (361,019.98)
	18%	$ (475,604.02)	$ (449,312.76)	$ (423,021.51)	$ (396,730.25)
	20%	$ (498,511.96)	$ (474,593.89)	$ (450,675.82)	$ (426,757.75)
	22%	$ (518,027.93)	$ (496,120.29)	$ (474,212.66)	$ (452,305.03)
	24%	$ (534,843.35)	$ (514,654.87)	$ (494,466.39)	$ (474,277.91)
	26%	$ (549,482.84)	$ (530,777.28)	$ (512,071.72)	$ (493,366.16)
	28%	$ (562,348.86)	$ (544,932.82)	$ (527,516.78)	$ (510,100.73)
	30%	$ (573,753.46)	$ (557,467.17)	$ (541,180.88)	$ (524,894.59)

	Cost of Electricity ($/kWhr)				
	$ (597,775.25)	**0.12**	**0.125**	**0.13**	**0.135**
Discount Rate (%)	**0%**	$ 635,575.48	$ 733,810.12	$ 832,044.76	$ 930,279.40
	2%	$ 379,011.44	$ 459,325.30	$ 539,639.15	$ 619,953.01
	4%	$ 187,316.57	$ 254,068.61	$ 320,820.65	$ 387,572.69
	6%	$ 41,735.47	$ 98,072.65	$ 154,409.83	$ 210,747.01
	8%	$ (70,617.74)	$ (22,393.63)	$ 25,830.48	$ 74,054.59
	10%	$ (158,703.65)	$ (116,887.30)	$ (75,070.96)	$ (33,254.62)
	12%	$ (228,828.10)	$ (192,140.20)	$ (155,452.29)	$ (118,764.39)
	14%	$ (285,481.50)	$ (252,950.46)	$ (220,419.42)	$ (187,888.38)
	16%	$ (331,899.10)	$ (302,778.23)	$ (273,657.35)	$ (244,536.47)
	18%	$ (370,438.99)	$ (344,147.74)	$ (317,856.48)	$ (291,565.22)
	20%	$ (402,839.68)	$ (378,921.61)	$ (355,003.54)	$ (331,085.46)
	22%	$ (430,397.40)	$ (408,489.77)	$ (386,582.14)	$ (364,674.50)
	24%	$ (454,089.43)	$ (433,900.95)	$ (413,712.47)	$ (393,523.99)
	26%	$ (474,660.60)	$ (455,955.04)	$ (437,249.48)	$ (418,543.92)
	28%	$ (492,684.69)	$ (475,268.65)	$ (457,852.60)	$ (440,436.56)
	30%	$ (508,608.30)	$ (492,322.00)	$ (476,035.71)	$ (459,749.42)

Table 17: Two-Dimensional Sensitivity Analysis – Discount Rate, Electricity Cost and Net Present Values – Electricity and Heat (Negative NPVs are shaded)

	Cost of Electricity ($/kWhr)				
	$ (597,775.25)	**0.055**	**0.06**	**0.065**	**0.07**
Discount Rate (%)	**0%**	$ (23,145)	$ 75,090	$ 173,325	$ 271,559
	2%	$ (159,540)	$ (79,226)	$ 1,088	$ 81,402
	4%	$ (260,295)	$ (193,543)	$ (126,790)	$ (60,038)
	6%	$ (336,038)	$ (279,701)	$ (223,364)	$ (167,026)
	8%	$ (393,988)	$ (345,764)	$ (297,540)	$ (249,316)
	10%	$ (439,106)	$ (397,290)	$ (355,474)	$ (313,657)
	12%	$ (474,842)	$ (438,154)	$ (401,466)	$ (364,778)
	14%	$ (503,621)	$ (471,090)	$ (438,559)	$ (406,028)
	16%	$ (527,171)	$ (498,051)	$ (468,930)	$ (439,809)
	18%	$ (546,737)	$ (520,446)	$ (494,155)	$ (467,863)
	20%	$ (563,224)	$ (539,306)	$ (515,388)	$ (491,470)
	22%	$ (577,301)	$ (555,393)	$ (533,486)	$ (511,578)
	24%	$ (589,465)	$ (569,276)	$ (549,088)	$ (528,899)
	26%	$ (600,092)	$ (581,387)	$ (562,681)	$ (543,976)
	28%	$ (609,469)	$ (592,053)	$ (574,637)	$ (557,221)
	30%	$ (617,817)	$ (601,531)	$ (585,245)	$ (568,958)

	Cost of Electricity ($/kWhr)				
	$ (597,775.25)	0.075	0.08	0.085	0.09
Discount Rate (%)	0%	$ 369,794	$ 468,028	$ 566,263	$ 664,498
	2%	$ 161,716	$ 242,030	$ 322,344	$ 402,657
	4%	$ 6,714	$ 73,466	$ 140,218	$ 206,970
	6%	$ (110,689)	$ (54,352)	$ 1,985	$ 58,322
	8%	$ (201,092)	$ (152,868)	$ (104,644)	$ (56,420)
	10%	$ (271,841)	$ (230,025)	$ (188,208)	$ (146,392)
	12%	$ (328,090)	$ (291,402)	$ (254,714)	$ (218,026)
	14%	$ (373,497)	$ (340,966)	$ (308,435)	$ (275,904)
	16%	$ (410,688)	$ (381,567)	$ (352,446)	$ (323,325)
	18%	$ (441,572)	$ (415,281)	$ (388,990)	$ (362,698)
	20%	$ (467,552)	$ (443,634)	$ (419,716)	$ (395,798)
	22%	$ (489,670)	$ (467,763)	$ (445,855)	$ (423,947)
	24%	$ (508,711)	$ (488,522)	$ (468,334)	$ (448,146)
	26%	$ (525,270)	$ (506,564)	$ (487,859)	$ (469,153)
	28%	$ (539,805)	$ (522,389)	$ (504,973)	$ (487,557)
	30%	$ (552,672)	$ (536,386)	$ (520,100)	$ (503,813)

Table 18: Two-Dimensional Sensitivity Analysis – Incentives and Grants, Fuel Cell Cost and Net Present Values – Electricity Only (Negative NPVs are shaded)

	FC Cost ($/kW)					
Incentives and Grants ($/kW)	(597,775.25)	2500	3000	3500	4000	4500
	0	$ (597,775.25)	$ (697,775.25)	$ (797,775.25)	$ (897,775.25)	$ (734,565.62)
	500	$ (497,775.25)	$ (597,775.25)	$ (697,775.25)	$ (797,775.25)	$ (634,565.62)
	1000	$ (397,775.25)	$ (497,775.25)	$ (597,775.25)	$ (697,775.25)	$ (534,565.62)
	1500	$ (297,775.25)	$ (397,775.25)	$ (497,775.25)	$ (597,775.25)	$ (434,565.62)
	2000	$ (197,775.25)	$ (297,775.25)	$ (397,775.25)	$ (497,775.25)	$ (334,565.62)
	2500	$ (97,775.25)	$ (197,775.25)	$ (297,775.25)	$ (397,775.25)	$ (234,565.62)
	3000	$ 2,224.75	$ (97,775.25)	$ (197,775.25)	$ (297,775.25)	$ (134,565.62)
	3500	$ 102,224.75	$ 2,224.75	$ (97,775.25)	$ (197,775.25)	$ (34,565.62)
	4000	$ 202,224.75	$ 102,224.75	$ 2,224.75	$ (97,775.25)	$ 65,434.38
	4500	$ 302,224.75	$ 202,224.75	$ 102,224.75	$ 2,224.75	$ 165,434.38
	5000	$ 402,224.75	$ 302,224.75	$ 202,224.75	$ 102,224.75	$ 265,434.38

Table 19: Two-Dimensional Sensitivity Analysis – Incentives and Grants, Fuel Cell Cost and Net Present Values – Electricity and Heat (Negative NPVs are shaded)

	FC Cost ($/kW)					
Incentives and Grants ($/kW)	(597,775.25)	2500	3000	3500	4000	4500
	0	$ (334,565.62)	$ (434,565.62)	$ (534,565.62)	$ (634,565.62)	$ (734,565.62)
	500	$ (234,565.62)	$ (334,565.62)	$ (434,565.62)	$ (534,565.62)	$ (634,565.62)
	1000	$ (134,565.62)	$ (234,565.62)	$ (334,565.62)	$ (434,565.62)	$ (534,565.62)
	1500	$ (34,565.62)	$ (134,565.62)	$ (234,565.62)	$ (334,565.62)	$ (434,565.62)
	2000	$ 65,434.38	$ (34,565.62)	$ (134,565.62)	$ (234,565.62)	$ (334,565.62)
	2500	$ 165,434.38	$ 65,434.38	$ (34,565.62)	$ (134,565.62)	$ (234,565.62)
	3000	$ 265,434.38	$ 165,434.38	$ 65,434.38	$ (34,565.62)	$ (134,565.62)
	3500	$ 365,434.38	$ 265,434.38	$ 165,434.38	$ 65,434.38	$ (34,565.62)
	4000	$ 465,434.38	$ 365,434.38	$ 265,434.38	$ 165,434.38	$ 65,434.38
	4500	$ 565,434.38	$ 465,434.38	$ 365,434.38	$ 265,434.38	$ 165,434.38
	5000	$ 665,434.38	$ 565,434.38	$ 465,434.38	$ 365,434.38	$ 265,434.38

Table 20: One-Dimensional Sensitivity Analysis – Interval of Fuel Cell Stack Replacements and Net Present Values: Three Cost Scenarios (Negative NPVs are shaded)

Interval of Fuel Cell Stack Change (cost $200,000)		
	Electricity Only	**Electricity and Heat**
years	**NPV**	**NPV**
5	$ (652,824.24)	$ (390,385.39)
6	$ (616,245.62)	$ (360,590.06)
7	$ (558,950.78)	$ (295,741.16)
8	$ (540,480.21)	$ (277,270.59)
9	$ (524,444.19)	$ (261,234.56)
10	$ (480,761.57)	$ (217,551.94)

Interval of Fuel Cell Stack Change (cost $250,000)		
	Electricity Only	**Electricity and Heat**
years	**NPV**	**NPV**
5	$ (715,117.08)	$ (451,907.45)
6	$ (669,393.79)	$ (406,184.17)
7	$ (597,775.25)	$ (334,565.62)
8	$ (574,687.00)	$ (311,477.41)
9	$ (554,642.01)	$ (291,432.38)
10	$ (500,038.73)	$ (236,829.10)

Interval of Fuel Cell Stack Change (cost $300,000)		
	Electricity Only	**Electricity and Heat**
years	**NPV**	**NPV**
5	$ (777,409.91)	$ (514,200.28)
6	$ (722,541.97)	$ (459,332.34)
7	$ (636,599.72)	$ (373,390.09)
8	$ (608,893.86)	$ (472,913.52)
9	$ (584,839.83)	$ (321,630.20)
10	$ (519,315.90)	$ (256,106.27)

6.1.5 Contribution of Government and Non-Government Incentives

The United States Internal Revenue Services currently allows corporations and utilities to claim tax credits in the amount of $500 per 0.5 kW of fuel cell operational capacity up to 30% of the total renewable energy project cost. California, New York, and Connecticut currently offer the most financial aid for renewable energy projects (including fuel cells) in the form of grants and tax incentives ranging from one cent per generated kWh of renewable energy tax credits to $2,000,000 grants. (DSIRE 2007) Unfortunately, grants are limited and competitively sought after. Many federal and state level programs operate on appropriated funds that are often consumed quickly. Additionally, some incentive programs do not include ADG consumption.

It is clearly visible in the net present value calculations in Sections 6.1.2, 6.1.3, and 6.1.4 how financially important government and non government incentives are when performing a cost assessment to consider installing a modified PC 25 C fuel cell power plant at a wastewater treatment plant. When the $1000 per kW of fuel cell operational capacity federal tax credit incentive is removed from the previous cost evaluations, the net present values decrease by an additional $200,000.

6.2 Qualitative Assessment: Intangible and Less Tangible Benefits from Utilizing the Modified PC 25 C Fuel Cell Power Plant at Wastewater Treatment Plants

There are many intangible and less tangible benefits of utilizing a modified fuel cell power plant to consume anaerobic digester gas at wastewater treatment plants. Some of these qualitative benefits were the ultimate reasons behind the NYPA installing eight fuel cell power plants at the four wastewater treatment facilities in New York City. During the research for this thesis, the following benefits were cited in literature and during interviews:

- The modified PC 25 C provides a method of capturing and utilizing a free, renewable biogas in an environmentally friendly manner.
- Fuel cell power plants reduce harmful emissions by removing contaminants from the ADG in a specially designed gas pretreatment unit before chemically reforming and chemically consuming available fuel.
- The modified PC 25 C fuel cell power plant reduces emissions by eliminating the need to flare ADG and by displacing utility-generated electricity.
- These units can provide reliable, utility grade electricity and heat for vital operations. In some cases, the installation of a fuel cell power plant, such as the PC 25 C, can be partially accounted for as a back up power source, offsetting the cost of a generator.
- These fuel cells can serve to improve or maintain an organization's green public image.
- These fuel cells are virtually silent as they operate, minimizing sound pollution.
- Distributed power applications, such as the Yonkers demonstration project, assist in keeping electricity costs lower for consumers of electricity from the electrical grid and natural gas. This is due the effective decrease in stress and demand on the public power utilities and transmission infrastructure. Additionally, distributed power helps to defer costly infrastructure improvements to meet societies growing electricity needs.

- As this technology is adopted at more WWTP locations, the technology will mature, and the production of these units will increase and effectively serve to help lower the cost of this technology. Each of these units installed benefits the fuel cell market as a whole by helping to develop and mainstream the technology.

6.3 Stakeholder Input: Additional Improvements

Many improvements and alterations have been made to the make the modified PC 25 C fuel cell power plant more environmentally friendly, user friendly, and operationally efficient. These alterations have primarily been engineered based on lessons learned from past and current projects. During interviews with stakeholders of this technology, specifically NYPA project managers, NYSERDA project managers, UTC Power Representatives, and US EPA Representatives, the following were cited as improvements or changes that still need to be made in order to increase and improve the use of the PC 25 C fueled by ADG:

- A substantial decrease in retail and installation cost must occur in order to make this technology more cost effective (Sliker 2007).
- A standard procedure must be derived for connecting distributed energy units to the electrical grid to avoid project delays and unnecessary man hours (Sliker 2007).
- The fuel cell stacks must be engineered to last longer than five to seven years. (Trocciola 2007) UTC Power anticipates unveiling a new cell stack in 2008 designed to effectively last 10 years (Purcell 2007).
- Chromium was detected in effluent from cell stack thermal management washes at several of the New York City emission offset projects. The source of this chromium needs to be identified and eliminated to make this technology more environmentally friendly (Sliker 2007).
- Federal and state renewable energy incentives must increase in areas where electricity costs and natural gas costs are lower to initiate interest in this technology (Spiegel 2007).
- Federal and state renewable energy incentives must increase in order to facilitate the use of this technology in all areas of the country. As the volume of fuel cells produced increases, the technology will become less expensive (Trocciola 2007).

- Organizations (government and NGOs) such as the NYPA and NYSERDA need to work with multiple companies that produce fuel cells to foster competitive manufacturing (Spiegel 2007).
- Service crews that are familiar with this technology need to be more widespread and more readily available to maximize fuel cell availability (Sliker 2007).
- Reliable, self-maintaining ADG pressure control valves and ADG delivery systems must be engineered and employed in conjunction with the fuel cell power plants. As previously mentioned, most of the ADG availability issues suffered at the four NYPA emissions offset projects were due to malfunctions in the ADG supply pipeline and pressure controls, not the GPUs or PC 25 C fuel power plants.
- In the future as more hydrogen appliances and hydrogen fueled cars are developed and put into mainstream use, it is the opinion of Ron Spiegel of the USEPA that fuel cell power plants should be utilized not only to produce electricity and heat but to generate hydrogen for use in other appliances. This scenario will require additional valving, hydrogen storage vessels, and distribution capabilities. The supply and demand of hydrogen gas will govern this dual capability evolution.

7.0 Discussion

Wastewater treatment plants are designed and operated with the sole purpose of treating sanitary, municipal, and industrial wastewaters. Anaerobic digestion gas is a byproduct of the wastewater treatment process, not the intended product. Wastewater treatment operators do not adjust processes to generate target volumes of ADG or manipulate the composition of the gas. Because of this simple fact, there is a high amount of variability in the amount and composition of ADG. Anaerobic digestion gas is viewed as a free, renewable biogas. Currently, there are over 400 wastewater treatment plants in the United States that utilize anaerobic digestion that are viable candidates for installation of at least one fuel cell power plant module operated on ADG (Spiegel 2003, 709).

Every fuel cell power plant installation is custom. The cost varies from site to site based on several factors, including facility layout (availability of space), ADG availability, location of the site, and project delays. Aspects, such as climate variability and alternative uses of ADG, are important factors when considering variations in the heat and electricity needs of wastewater treatment plants.

When performing a cost assessment of this technology, it is important to note that at more than 95% of facilities utilizing anaerobic digestion, ADG is already consumed at some capacity in onsite electricity or heat generation (Trocciola 2007). At most locations, ADG is combusted in boilers at a nearly 90% thermal efficiency to generate heat for use at the facility. ADG that is not required for heat generation in the boilers are flared off. ADG is also consumed in micro turbines for electricity generation at facilities where large quantities of ADG are available. During interviews with Guy Sliker of the NYPA and John Trocciola, formerly of UTC Power, it was revealed that heat generated from this technology at wastewater treatment plants is inefficiently utilized. In some cases, such as the Red Hook WWTP, the heat is not used at all. It was the opinion of John Trocciola that when performing a cost assessment of this technology, the available heat should not be considered (2007).

Previous sections of this report have demonstrated through economic assessment that at present, the installation of a PC 25 C fuel cell power plant at a wastewater treatment facility is not economically effective at the US industrial average electricity cost of \$0.0675. Sections 6.1.2 and 6.1.3 demonstrate largely negative net present values when considering two scenarios: the usage of generated electricity only (NPV of -\$597,775.25) and then usage of both generated electricity and heat (NPV of -\$334,565.62). NPV is an indicator of how much value an investment or project adds to an organization. Generally, negative net present values are an indicator that a project should not be undertaken.

During conversation with interviewees, it was largely agreed upon that this technology has not reached a mature status and is still very expensive to purchase. This was attributed to the low number of these units that are manufactured yearly (Trocciola 2007). Currently, twenty to twenty-five PC 25 C fuel cell power plants are produced by UTC Power per year (Trocciola 2007).

There is sharply increasing demand for energy around the world. Since the beginning of 2005, light crude oil prices have increased from approximately \$50 per barrel to nearly \$100 per barrel (money.cnn.com). Electricity prices have increased approximately \$0.01 to \$0.03 cents per kWh in the United States from July of 2006 to July of 2007 (EIA 2007). In the future, it seems likely that energy prices will continue to increase. As electricity and natural gas prices rise, the net present values of installing and utilizing this technology will increase. Table 11 demonstrates that the net present value for the installation and utilization of this technology when utilizing electricity only is positive when the cost of electricity is greater than \$0.135 per kWh. The net present value, when utilizing both electricity and heat, is positive when the cost of electricity is greater than \$0.11 per kWh. According to Guy Sliker in a 2007 interview, based on his actual recorded costs over the life of the four emissions offset projects in New York City, he estimated that \$0.13 per kWh was the electricity cost at which the fuel cell power plants would become cost effective. This closely correlates to the research findings in this thesis.

According to the July 2007 average electricity prices to large industrial customers, Connecticut, Massachusetts and New Jersey represent markets where it is cost effective to utilize this technology. These states have industrial electricity costs of greater than \$0.13 per kWh. Maine, New Hampshire, Rhode Island, New York, Washington D.C., Nevada, and California follow closely behind these states with industrial electricity rates ranging from \$0.0958 to \$0.1244 per kWh (See Appendix D).

In New York, Connecticut, and California, large grants and production incentives are available from government and non government operated organizations. In New York State, for example, NYSERDA offers up to \$2,000,000 or 50% total project costs, for combined heat and power (CHP) projects. In Connecticut, the Connecticut Clean Energy Fund offers a maximum of \$4,000,000 per project plus additional production incentives for CHP projects. In addition, the federal government offers a production incentive of \$0.015 per kWh of generated electricity for distributed fuel cells using renewable fuels. As previously mentioned, however, these are appropriated funds that are competitively sought after and not guaranteed.

Without financial support from federal, state, and non-government organizations, this technology is less economically viable. Sections 6.1 through 6.4 demonstrate the importance of financial support for these projects. For the purpose of the two point estimate cost assessments, a federal tax incentive of \$500 per 0.5 kW of operational fuel cell capacity was included in the calculations. When this incentive is removed from the analysis, utilizing generated electricity only, the cost of electricity at which the net present value becomes positive (quantitatively viable) is between \$0.16 and \$0.17 per kWh. Only one state has electricity rates higher than this for large industrial customers: Hawaii.

When performing a two dimensional analysis to examine the effect on the net present value of changing both the fuel cell cost and incentives and grants (Table 19), the results demonstrated that when the average fuel cell cost is \$3500 per kWh capacity, government and non-government organizations must provide approximately \$3000 per kWh of fuel cell capacity to make the net present value of this technology positive. As the fuel cell cost decreases, the required incentives and grants also decrease. Currently, the federal government offers a tax incentive of $500 per $0.5 kW of installed fuel cell capacity.

When wastewater treatment plants effectively utilize the heat generated from the PC 25 C, the cost of natural gas can be figured into the net present value calculations. Table 15 is a one dimensional sensitivity analysis that explores the effect on the net present value of changing the cost of natural gas. As the price of natural gas increases, the net present value of installing this technology also increases.

As discussed in 6.1, the discount rate used for the point estimate cost assessment was 10%. The discount rate is a financial term which accounts for the value of future cash flow in lieu of the present value of the cash flow. Essentially, it is the future opportunity value of an investment. For a renewable energy project, a discount rate of 8% to 12% is appropriate based on the moderate to high level of uncertainty and riskiness of the project. In section 6.1.4, a sensitivity analysis was performed to examine the effect of changing the discount rate on the net present value. As suspected, the net present value increases as the discount rate decreases. Also, as the price of electricity increases, the net present value becomes higher at incrementally higher discount rates (see Table 16). When assuming best case and worst case scenarios of 8% and 12% for this technology when utilizing electricity only, the net present values become positive at electricity costs of $0.13 and $0.15, respectively.

Quantitative assessments are not the only factors that are considered when installing this technology at a wastewater treatment plant. Section 6.2 outlines many of the qualitative benefits of utilizing this technology. There are circumstances where the less tangible benefits are valued by a facility or organization such that they can outweigh cost assessment. The NYPA chose to install eight fuel cell power plant units at four wastewater treatment facilities, not for their cost-effectiveness, but to offset emissions from the installation of multiple natural gas electrical turbines. Specifically pertaining to

ADG at municipal wastewater treatment plants, reduced flaring and emissions offset, public image maintenance, and silent operation are very important.

Section 6.3 demonstrates additional improvements which must be made to make this technology more economical, user friendly, and environmentally friendly. As previously mentioned, UTC power is currently developing a fuel cell stack that will have an effective life of 10 years (Purcell 2007). Table 20 summarizes the relationship between net present value and fuel cell replacement intervals. It is visible, that as the interval increases between fuel cell stack replacements, the net present value becomes less negative. Based on this sensitivity analysis, one fuel cell replacement at 10 years at a cost of $250,000 is the most cost-effective scenario.

Because this technology is not mainstream, installation procedures and utility connection agreements have not been standardized. This means that each project that is undertaken is a learning process and subsequently takes longer to accomplish because standard procedures have not been established. Additionally, there are few trained service technicians that can effectively maintain this technology.

The ADG gas pipelines and pressure valves must be better maintained at the wastewater treatment facilities. As described earlier, malfunctions of these systems were responsible for the majority of fuel cell availability problems. As the fuel cell availability is bettered, the unit will be operation for more hours of the year, and the overall value of the unit will increase.

In order to make this fuel cell technology more economically viable, federal and state incentives must increase in areas where electricity costs and natural gas costs are lower to initiate interest in this technology (Spiegel 2007). The focus cannot only be on regions where electricity and natural gas prices are high. With additional incentives, this technology will be utilized more at wastewater treatment plants, which will result in higher production rates, and subsequently influence a slow decrease in the price of these units.

8.0 Conclusions

8.1 Thesis Conclusions

In 1999, a cost benefit analysis of installing and utilizing a modified PC 25 C fuel cell power plant consuming anaerobic digestion gas was performed. It was completed to provide support for the Yonkers demonstration project. At the time of its publication, the average cost of electricity to large industrial customers was $0.05 per kWh. The estimated combined retail and installation cost of the fuel cell was $3000 per kW and $0.015 to operate and maintain. It was further estimated that the GPU would cost $100 per kW and $0.015 per kWh to operate and maintain. Utilizing these figures and assuming that all heat generated from the power plant was to be used onsite, the PC 25 C fuel cell power plants were deemed to be economically viable (Spiegel 1999).

After discussion with two of the authors that participated in this document, there were several optimistic assumptions that were made during the 1999 cost benefit analysis:

- Several appropriated government incentives were not received during the project: distributed power credit, backup power avoidance credits, and emissions credits.
- In hindsight, many of the associated costs were much higher than expected due to the immaturity of the technology (Spiegel 2007).

Since the publication of this cost benefit analysis in Spiegel's "Fuel Cell Operation on Anaerobic Digester Gas: Conceptual Design and Assessment", more focus has been placed on the functionality and effective emissions reductions from utilizing this technology. Approximately one year of thorough archival research did not produce other documents discussing cost assessments. Ron Spiegel of the EPA and John Trocciola, formerly with UTC Power, did not know of the existence of other formerly published cost assessments (2007). The lack of cost benefit information immediately after the beginning of the Yonkers demonstration project suggests that the project was economically disappointing. This document effectively assembles important variables and analyzes the cost effectiveness of utilizing this technology at wastewater treatment plants.

From a strictly quantitative approach, the PC 25 C fuel cell power plants operating on ADG at wastewater treatment plants are not economically viable investments in most parts of the country. However, the northeastern United States, several states in the western United States and the Pacific noncontiguous states represent viable markets for utilization of this technology due to high electricity costs. Federal and state program grants, tax incentives, and renewable energy production incentives are available to help defer the initial project cost and potentially make this technology a viable investment. These funds, however, may be tough to acquire because some are appropriated and highly competitive. Overall, financial support from government and non government organizations is crucial to the utilization and further development of this technology.

The qualitative benefits derived from installing this technology can take precedence over quantitative short comings. In certain circumstances, such as the four emissions offset projects in New York City, this technology was employed because of the qualitative benefits derived, not the cost effectiveness.

One variable that cannot be controlled when selecting a wastewater treatment plant for the installation of a modified PC 25 C is the variability of the volume and composition of the ADG supply. When selecting a project site, a study should be done to measure this variable to ensure a sufficient supply of ADG is available. As stated in previous sections, the minimum amount of ADG production that will operate a PC 25 C fuel cell power plant is a nominal ADG flow of 3,600 ft^3 per hour with at least 60% methane content. Lower methane content (down to 50%) can be utilized at higher pressure and gas flow (Purcell 2007). Alternatively, the cost of partial natural gas operation needs to be considered and figured into the project plan.

Section 6.3 is an outline of stakeholder recommendations to further improve this technology. The additional improvements suggested by stakeholders during interviews demonstrate an active interest in making the fuel cells more economically viable, improving fuel cell performance (availability and fuel cell capacity) to make the units more valuable, and making the units more environmentally friendly. Of all the suggested improvements, the most productive would be to improve the ADG supply pipelines. It was noted that more reliable, self-maintaining pressure control valves and ADG delivery systems must be engineered and employed in conjunction with the fuel cell power plants. Most of the ADG availability issues suffered at the four NYPA emissions offset projects were due to malfunctions in the ADG supply pipeline and pressure controls, not the GPUs or PC 25 C fuel power plants. This improvement would effectively serve to increase both the availability and fuel cell capacity.

8.2 Concluding Remarks and Future Research Potential

Utilizing hydrogen as an energy carrier is one of the keys to meeting the world's increasing energy demand. Hydrogen when combined with oxygen produces water and energy. The technology described in this thesis does utilize hydrogen energy technology, but it also uses an organic fuel that releases carbon dioxide into the atmosphere during energy production. It has been demonstrated that utilizing ADG in a fuel cell power plant does decrease emissions and eliminates the need for wasteful flaring. However, optimism remains that this technology will one day be utilized to support a hydrogen economy supported mostly by hydrogen liberated from water in hydrogen appliances partnered with clean, renewable energy sources, such as hydro, solar, or wind power. A hydrogen economy based on the reforming of solid, liquid, or gaseous hydrocarbons may assist in lessening our reliance upon foreign nations for fuel, but will not assist in slowing global warming.

The positive economic results discovered during this study were unexpected. Preliminary interviews with project managers from various government sponsored organizations spoke very pessimistically about the cost effectiveness of utilizing this technology at a wastewater treatment plant to consume ADG. The suspected explanation of this is that the five wastewater treatment plants studied in this work are located in New York City and the surrounding region. The average New York State electricity price to large industrial customers is right on the borderline of being cost effective. These projects were also undertaken at a time when this technology was very immature and expensive.

Further areas of research regarding the utilization of modified fuel cell power plants to consume ADG include:

- Exploring the use of this technology at landfills and farms. Although this technology may be viable at wastewater treatment plants, preliminary research demonstrates that it is less functionally reliable and not economically viable at land fills and farms.
- Attempting to quantify the qualitative benefits mentioned in this thesis. A study can be performed to determine willingness-to-pay or willingness-to-avoid benefits associated with this technology. The cost assessment in this document can be expanded upon to include these values.
- Identifying more clearly the emissions offset and emission reductions from utilizing this technology. The electricity supply source in the United States varies by region. Many eager emissions reductions estimates uncovered during this research were based on emissions from coal fired power plants.

Works Cited:

Allen, Matthew R., Alan Braithwaite, and Chris C. Hills. "Trace Organic Compounds in Landfill Gas At Seven U.K. Waste Disposal Sites." *Environmental Science and Technology* 31 (1997): 1054-1061.

"Anaerobic Digestion." *California Energy Commission*. 27 Apr. 2005. Fall 2007 < www.energy.ca.gov/development/biomass/anaerobic.html>.

"Annual Energy Outlook 2006 with Projections to 2030." *Energy Information Administration*. Feb. 2006. 31 July 2006 <www.eia.doe.gov/oiaf/aeo/demand.html>.

Answers.Com. Summer 2006 <www.answers.com>.

Bossel, Ulf, Baldur Eliasson, and Gordon Taylor. "The Future of the Hydrogen Economy: Bright or Bleak?" *Cogeneration and Distributed Generation Journal* 18 (2003): 29-70.

"Capitalizing on the Waste From Waste Treatment." *New York Power Authority*. Fall 2007 <http://www.cleanair-coolplanet.org/information/pdf/ny-power-authority.pdf>.

CNN Money. Fall 2007 <http://money.cnn.com/>.

Database of State Incentives for Renewables & Efficiency (DSIRE). Fall 2007 <www.dsireusa.org>.

"Draft Business Plan of ISO/TC 197 - Hydrogen Technologies." *International Organization for Standardization*. 06 June 2001. 31 July 2006 <http://isotc.iso.org/livelink/livelink/fetch/2000/2122/138465/138466/1075133/N196_-Fourth_version_of_the_ISO_TC_197_business_plan.pdf?nodeid=1223243&vernum=0>.

Dunn, Seth. *Hydrogen Futures: Toward a Sustainable Energy System*. Ms. 157. Worldwatch Institute, Washington, DC. 2001.

Elhefnawy, Nader. "Toward a Long-Range Energy Security Policy." *Parameters* (2006): 101-114.

Entrix Environmental Consultants. Summer 2006 <www.entrix.com>.

Greenhouse Gas Technology Center, United States Environmental Protection Agency, *Electric Power and Heat Generation Using the UTC Fuel Cells' PC 25 C Power Plant and Anaerobic Digester Gas*, SRI/USEPA-GHG-VR-26, September 2004.

Haynes, Rusty. *Financial Incentives for Stationary Fuel Cells: A Report on State-Level Policy in the United States.* Ms. North Carolina Solar Center, Raleigh, NC. 2004.

Kishinevsky, Yan, and Shalom Zelingher. "Coming Clean with Fuel Cells, an Innovative Emission-Offset Project That Utilizes Anaerobic Digester Gas-Powered Fuel Cells to Produce Electricity." *Power and Energy Magazine* 6 (2003): 20-25.

Kishinevsky, Yan. *Operation of a 200-KW PAFC Unit on Anaerobic Digestor*. Interim Report. TR-109153. 1997.

Kruse, Bjørnar, Sondre Grinna, and Cato Buch. "Hydrogen: Status og muligneter." *Bellona Rapport* 6 (2002): 1-52. http://bellona.org/filearchive/fil_Hydrogen_6-2002.pdf

Lovins, Amory. *Twenty Hydrogen Myths*. Ms. E03-05. Rocky Mountain Institute, Snowmass, CO. 2005.

Lovins, Amory B., and Chris Lotspeich. "Energy Surprises for the 21st Century." *Journal of International Affairs* 53 (1999): 192-208.

Lovins, Amory B., and L. Hunter Lovins. "Energy Forever." *The American Prospect* 13 (2002): 30-34.

Lovins, Amory B., and Brett D. Williams. *A Strategy for Hydrogen Transition*. 10th Annual U.S. Hydrogen Meeting, 7-9 Apr. 1999, National Hydrogen Association.

Mazza, Patrick and Roel Hammerschlag. *Carrying the Energy Future: Comparing Hydrogen and Electricity for Transmission, Storage and Transportation*. Ms. Institute for Lifecycle Environmental Assessment, Seattle, WA. 2004.

Mulik, Katie. *"Does Hydrogen Fuel Pose Environmental Problems?" Online NewsHour* 20 Oct. 2003. Summer 2006 <http://www.pbs.org/newshour/science/hydrogen/environment.html>.

National Hydrogen Energy Roadmap. United States Department of Energy. 2002. 1-56. Summer 2006 <http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/national_h2_roadmap.pdf>.

"NFCRC Tutorial: Phosphoric Acid Fuel Cell (PAFC)." *National Fuel Cell Research Center*. Fall 2007 <http://www.nfcrc.uci.edu/EnergyTutorial/pafc.html>.

"New Technology Programs." *New York Power Authority*. Fall 2007 <http://www.nypa.gov/services/fuel%20cells.htm>.

New York State Energy Research and Development Authority. "1.6 MW Fuel Cell Distributed Generation Project Utilizing Renewable Anaerobic Digester Gas, Cofunding Agreement No. 6937, Summer 2006.

New York State Energy Research and Development Authority. “New York State Hydrogen Energy Roadmap” October 2005 <http://www.energetics.com/meetings/nyhydrogen/pdfs/roadmap.pdf

New York State Energy Research and Development Authority. “Hydrogen Fact Sheet: History of Hydrogen” Summer 2006. <http://www.getenergysmart.org/Files/HydrogenEducation/3HistoryofHydrogen.pdf>

O'Leary, Brian. "Energy Alternatives That Save the World." June 2003. Summer 2006 <http://home.independence.net/oleary/Energy%20Alternatives.htm>.

Purcell, Homer. UTC Power. Telephone interview. 2 Oct. 2007.

Pyle, Walt, Jim Healy, and Reynaldo Cortez. “Solar Hydrogen Production by Electrolysis.” *Home Power* 39 (1994): 32-38.

Shaw, Betsy. "Environmental Stewardship." *Environmental Council of the States*. Summer 2006 <http://www.ecos.org/files/1603_file_ECOSStewardshipHandout1.doc>.

Sibelrud, Robert. *Our Future is Hydrogen!* Wellington, Colorado: New Science Publications, 2001.

Sliker, Guy. New York Power Authority. Telephone interview. 12 Oct. 2007.

Sliker, Guy. "Capitalizing on the Waste from Waste Treatment." Fall 2007 <www.cleanair-coolplanet.org/information/pdf/ny-power-authority.pdf>.

Sperling, Daniel, and Joan Ogden. *The Bumpy Road to Hydrogen*. Ms. World Hydrogen Energy Conference, Lyon, France. 2006.

Spiegel, Ronald J. United States Environmental Protection Agency. Telephone interview. 16 Oct. 2007.

Spiegel, Ronald J., and J L. Preston. "Technical Assessment of Fuel Cell Operation on Anaerobic Digester Gas at the Yonkers, NY, Wastewater Treatment Plant." *Energy* 28 (2003): 397-409.

Spiegel, Ronald J., S A. Thorneloe, John C. Trocciola, and J L. Preston. "Fuel Cell Operation on Anaerobic Digester Gas: Conceptual Design and Assessment." *Waste Management* 19 (1999): 389-399.

Staniunas, Joseph W. Email to the author. 6 Nov. 2007.

Strunz, Kai, and E. Kristina Brock. “Stochastic Energy Source Access Management: Infrastructure-integrative modular plant for sustainable hydrogen-electric cogeneration." *International Journal of Hydrogen Energy* 31 (2006): 1129-1141.

Swisher, Joel. *Cleaner Energy, Greener Profits: Fuel Cells as Cost-Effective Distributed Energy Resources*. Ms. Rocky Mountain Institute, Snowmass, CO. 2005.

Tierney, Robert. UTC Power. Telephone interview. 2 Oct. 2007.

Trocciola, John. Consultant. Telephone interview. 16 Oct. 2007.

United States Department of Energy. Summer 2006 <http://www1.eere.energy.gov/hydrogenandfuelcells/>.

United States Department of Energy. Fall 2007 < http://www.eia.doe.gov/oiaf/1605/ggccebro/chapter1.html>.

United States Environmental Protection Agency. *Compilation of Air Pollutant Emission Factors AP-42*. 5th ed. Vol. 1. North Carolina: United States EPA, 1995.

Wikipedia.com. Fall 2007 < http://en.wikipedia.org>.

Yacobucci, Brent, and Aimee Curtright. *A Hydrogen Economy and Fuel Cells: An Overview*. Ms. Congressional Research Service Report for Congress. 2004.

Zeltman, Eugene W. "Remarks from Speech Given At the Interstate Natural Gas Association of America Security Analysts' Conference, Colorado Springs, Colorado." 14 July 2001. <http://www.nypa.gov/press/speeches/2001/10714a.htm>.

Appendix A: Core Questionnaire for Interview Process

The following schedule will be followed through the interviewing process:

Pre- Interview:

- The contacts on the proposed interviewee list for this thesis will be contacted during regular business hours. Time zones will be taken into account when making contact. Phone calls and emails will be the primary method of contacting potential interviewees.
- Upon agreement to be interviewed, a core set of questions will be sent to the interviewee via email, facsimile, or mail. The preferred format of the interview (in-person or phone) will be discussed and a tentative date and time will be established.
- The interviewee will be contacted two days before the scheduled interview to confirm the availability of the interviewee on the previously agreed upon date and time.

The Interview:

- Introduction to myself and my thesis.
- Ask about the career history of the interviewee and ascertain his or her role significance to the demonstration project.
- Ask the interviewee if he or she would like to remain anonymous in my final thesis report.
- Ask the interviewee if I have permission to record our conversation.
- The interview will be conducted based on the list of questions included in this appendix.
- Once all core questions have been addressed, I will thank the interviewee.

Core Questions for the interview:

Basic operational questions about the facility will be asked for background purposes.

Why were these fuel cell power plants installed?

Have you (or more generalized, the WWTP) noticed cost savings as a result of implementing the ADG fuel cell? Essentially, are these units cost-effective to install and operate?

Is there enough benefit derived from this project that, without assistance from the government, WWTP’s could be convinced to install a system like this with their own capital expenditures?

Is there a minimum amount of ADG that must be generated at a WWTP to make this fuel cell system a viable investment?

Do you consume the energy generated from the fuel cell, or is some sold back into the grid? Essentially, is there income from this project?

Quantitative questions about costs, savings, tax advantages, and income will be asked of accountants/financial officers.

What physical improvements can or need be made to this system? Is there a specific part of the system which must be improved in order to make this a more viable solution?

Have you noticed a change in opinion from the public about your WWTP since you have implemented this project? Has there been feedback from the community? Please explain.

What recommendations do you have for other WWTP that are considering implementing a system such as this?

Post Interview

- After the interview has been undertaken and concluded, a transcript of the interview will be produced. Direct quotations and concepts from the interviews will be included in the final thesis.
- A thank you card will be sent to each interviewee for participation in the thesis.
- I will offer to send an electronic copy of the thesis to the interviewees.
- Upon request of the interviewee, the transcript of the interviews and electronic recordings will be destroyed.

The interviewing process will not be static. As this thesis evolves, the above questions may be adjusted. In addition, questions will be directed towards the expertise of the interviewee. All questions will not be appropriate for all of the interviewees. Section five (5.0) of this thesis outlines the expected results. Through interview, additional topics of interest may be uncovered and addressed in the final thesis.

Appendix B: Biographies of Interviewees

John Trocciola
Private Consultant
Former Manager of Advanced Materials and Development, UTC Power (formerly ONSI), South Windsor, CT

Mr. John Trocciola has served as a private consultant, both professionally and on a pro-bono basis, for a variety of potential fuel cell users in evaluating emerging and existing fuel cell technologies. These clients include UTC Power , US Department of Energy , US Department of Defense , US and Overseas electric utilities (Including NY Power Authority, Long Island Power Authority, and RWE). US and Overseas Natural Gas Companies such as KeySpan Energy, Energy East and Gazprom are also clients of Mr. Trocciola as well as Scripps Investments and Loans, Power Management Concepts, Ct Clean Energy Fund, Ct Department of Homeland Security, Massachusetts Technology Collaborative, Russian Nuclear Agency Rosatom, and the Town Government of Portland, CT.

Prior to working as a private consultant, Mr. Trocciola served a variety of roles at the United Technologies Corporation from 1963 - 2004. His position as Manager of Advanced Materials and Development allowed him to investigate the basic limits of materials for all fuel cell technologies including AFC, PEM, PAFC and MCFC, and to identify the fundamental thermodynamic properties of carbons, graphites and polymers which determine their suitability for use in fuel cells. In addition, he was active in performing Advanced System Analysis/Evaluation of all alternative fuel cell technologies of which he recommended PAFC for further development for commercial stationary fuel cells

As Program Manager of several NASA and DOD Programs for space and underwater fuel cell power plants, he was able to identify successful methods for supplying hydrogen and cooling fuel cells in harsh environments as well as methods to remove CO from hydrogen streams for PEM power plants.

One of Mr. Trocciola's most notable and innovative achievements occurred while working on several US Environmental Protection Agency projects where and others at UTC and the EPA identified and patented unique gas cleanup systems to treat the renewable gas to produce H2; this resulted in 12 fuel cell installations at waste water plants and landfills around the world. And it was during a joint DOE/DOD Program that he was responsible for the management of the installation and startup of the first commercial fuel cell in Russia located at a Gazprom facility in Moscow. This is the same commercial fuel cell that provided power during the Moscow blackout.

Mr. Trocciola received his Bachelor of Chemical Engineering from Manhattan College, a M.S. Degree in Chemical Engineering from the University of Connecticut and a M.S. in Mechanical Engineering from the University of Connecticut.

Mr. Trocciola is recognized as a fuel cell industry leader and his 40 US Patents in areas such as AFC, PAFC, MCFC, SOFC, and PEM show his enthusiastic innovation. He was recipient of many awards including the Special Inventors Award by NASA, the Technology Innovation Award by Discover Magazine, and the Outstanding Engineer Graduate Award given to him by Manhattan College.

Biography Source: http://www.fuelcellsworks.com/Supppage8008.html

Ronald Spiegel
Director of the National Risk Management Research Laboratory, United States Environmental Protection Agency, Research Triangle Park, NC

Dr. Spiegel received B.S. in electrical engineering from Georgia Tech and a Ph.D. in electrical engineering, with a minor in optical physics, from the University of Arizona. His Ph.D. dissertation dealt with the detection of atmospheric pollutants using laser radar techniques. Subsequent to graduation, he was a Post Doctoral Fellow in biomedical engineering at Duke University, where he conducted research in the interaction of electromagnetic fields with biological media.

After completing his fellowship, he held positions in private industry, including the Boeing Aerospace Company, and at research institutes, including the IIT Research Institute and Southwest Research Institute. Much of the work was military-related research in the areas of electromagnetic compatibility, nuclear electromagnetic pulse, radar cross-section analysis, and antennas.

In 1980, he joined EPA in the Office of Research and Development, Health Effects Research Laboratory, Research Triangle Park, NC, where he supervised a multi-disciplinary team of researchers with the mission of conducting research in the area of electromagnetic fields interaction with biological objects relating to experimental methods, dosimetric methods, model development, and mitigation approaches. He later moved to the National Risk Management Research Laboratory, where he is currently researching cutting-edge environmental technology development. This area includes fuel cell application to waste methane gases, intelligent control (fuzzy logic, neural networks, and genetic algorithms) of electric motors and wind turbines for enhanced performance and efficiency, and solar photovoltaics.

Ron is member of Sigma Xi and the Institute of Electrical and Electronic Engineers (IEEE). He was awarded EPA Scientific and Technological Achievement Awards in 1984, 1990, and 1998, and was a finalist in the 1996 Discover Magazine Awards for Technological Innovation. He has been awarded patents for research in fuel cell applications and in motor and wind turbine control.

Biography Source: http://www.epa.gov/appcdwww/apb/bio.htm

Homer Purcell
Vice President of Sales, UTC Power, South Windsor, CT

Technology Innovation Award by Discover Magazine, and the Outstanding Engineer Graduate Award given to him by Manhattan College.
Homer Purcell is vice president, sales, at UTC Power. Purcell is responsible for overseeing all sales activity for on-site power solutions, including stationary fuel cells and combined cooling, heating and power applications in the distributed energy market. He assumed his current position in October 2005.

Purcell has more than 30 years of experience in the power industry and its sales and marketing functions. Before joining UTC Power he was senior vice president, business development at InfraSource Services, Inc., where he led corporate sales, business partnerships, market development and communications. Previously, he served in leadership positions at Siemens PT&D, BICC Cables Company, ABB Power T&D Company and Westinghouse Electric Corporation.

Purcell received a Bachelor of Science degree in industrial engineering with honors from the University of Tennessee.

A native of Tennessee, Purcell and his wife have two children and live in Ramsey, New Jersey.

Biography Source:
http://www.utcpower.com/fs/com/bin/fs_com_Page/0,11491,059,00.html

Robert Tierney
Director, Sustainability & Government Programs, UTC Power, South Windsor, CT

Bob Tierney has worked for UTC/Pratt & Whitney since 1979. Currently, he directs sustainability and government programs for UTC Power. Previously, he was Director of Health and Safety for Pratt's global operations. Prior to that, he was manager of green business solutions in the Specialty Materials &: Services organization and prior to that he was manager in the engineering division leading the green engine program. Within UTC, Bob founded and leads the companiy's sustainability network.

Bob obtained a BS in environmental engineering from Florida Institute of Technology, an MBA from Florida Atlantic University, and a Masters of Environmental Studies from Yale University.

Biography Source: http://www.erb.umich.edu/People-and-Partners/Advisory-Board/

Guy Sliker
Program Manager for Distributed Energy Resources and Energy Utilization, New York Power Authority, New York, NY

Guy Sliker is the Program Manager for Distributed Energy Resources and Energy Utilization in the Research and Technology Development group of the New York Power Authority, the nation's largest state-owned power organization. Mr. Sliker has been working with distributed generation and renewable energy R&D fields for 15 years, primarily with public and private electric utility companies. At his current position at the New York Power Authority Mr. Sliker is responsible for the implementation of the company's distributed energy resource, renewable energy and hydrogen energy programs. In addition, Mr. Sliker is responsible for the long term operation of distributed generation projects throughout New York State. Mr. Sliker has a BA in Economics and an MS in Mechanical Engineering, both from the University of Massachusetts.

Biography Source:
http://www.neny.org/ContentManager/index.cfm?Step=Display&ContentID=121

John Love
Project Manager, New York State Energy Research and Development Authority (NYSERDA), Albany, NY

John Love is a project manager for the New York State Energy Research and Development Authority (NYSERDA) Industrial R&D Department. He has over 18 years of diversified engineering, sales and project management experience in the power and energy field. He received his bachelor's degree in Mechanical Engineering from Manhattan College and his master's degree in Business Administration from Union College.

Mr. Love manages the Emerging Technologies Program that acts to accelerate demonstration and commercialization of emerging energy technologies such as advanced controls and sensors and high temperature superconductivity. John's most recent activity is focused on establishing a hydrogen program for New York State.

Biography Source:
http://www.neny.org/ContentManager/index.cfm?Step=Display&ContentID=88

Mark Torpey
Senior Project Manager, New York State Energy Research and Development Authority (NYSERDA), Albany, NY

Mark Torpey is a Senior Project Manager with the New York State Energy Research and Development Authority (NYSERDA). Mark is responsible for managing NYSERDA's distributed generation (DG) program with a particular emphasis on combined heat and

power (CHP) applications. NYSERDA manages the DG/CHP program on behalf of the New York State Public Service Commission (NYSPSC) with $15 million in annual funding to support both product development and demonstration projects. Prior to his current position with NYSERDA, Mark worked for Plug Power as the Director of Government Relations. Plug Power is a New York based manufacturer of PEM fuel cells. Mark also worked for fourteen years at Foster Wheeler, a New Jersey based Architect Engineering firm, serving in his last position as Technical Director of Research and Development.
Mark has a Bachelor of Science in Mechanical Engineering from Brown University, and a Master of Science in Mechanical Engineering from MIT.

Biography Source: http://www.ashraeny.org/gbd040318/presenters.htm#mark2

Appendix C: Estimated Annual Emission Reductions.

The following equations are excerpted from the Environmental Protection Agency's 2004 Environmental Technology Verification Report titled "Electric Power and Heat Generation Using UTC Fuel Cells' PC 25 C Power Plant and Anaerobic Digester Gas".

Emission reductions are computed as follows:

Reduction (lbs) = $E_{GRID} + E_{FLARE} - E_{CHP}$
Reduction (%) = $(E_{GRID} + E_{FLARE} - E_{CHP})/(E_{GRID} + E_{FLARE}) * 100$

Where:

Reduction = Estimated annual emission reductions from on-site electricity generation, lbs or %
E_{CHP} = Estimated annual emissions from PC 25 C, lbs
E_{GRID} = Estimated annual emissions from utility grid, lbs
E_{FLARE} = Estimated annual emissions from flare, lbs

The following describes the methodology used.

Step 1 - Estimation of PC 25 C CO_2 and NO_X Emissions:

The first step in calculating emission reductions is to estimate the emissions associated with generating electricity with ADG at the site over a given period of time (one year), operating at normal site conditions. Based on the total electrical generation over the 30-day monitoring period (extrapolated to a one-year period), and the measured emission rated, the PC 25 C emissions can be estimate as follows:

$E_{CHP} = ER_{CHP} * kWh_{CHP}$

Where:
E_{CHP} = Estimated annual emissions from PC 25 C fueled with ADG, lbs
ER_{CHP} = PC 25 C CO_2 or NO_X emission rate at full load on ADG, lb/kWh
Wh_{CHP} = Total annual electrical energy generated at the site, kWh

Step 2 – Estimation of Utility Grid Emissions:

The grid emission rate (ER_{Grid}) is a complex subject, and the methodology for estimating it is continuously evolving. The Greenhouse Gas Center used the emission factors developed by the Ozone Transport Commission (OTC). The OTC emission factors for this region [the New York State Independent System Operator (NY ISO) region] are separated into ozone and non-ozone seasons as well as weekdays and night and weekend time periods. For this verification however, the center was not able to procure detailed facility demand data, and the PC 25 C extended monitoring period failed to provide a realistic estimate of annual PC 25 C generation (due to numerous outages caused by facility operations at Red Hook). Therefore, time weighted 2002 average emissions factors for the NY ISO are used here. They are 0.0023 lb/kWh for NOX, and 1.49 lb/kWh for CO_2. Estimated power grid emissions for equivalent power production, therefore, are based on the annual estimated kilowatt-hours generated by the PC 25 C, line losses, and the grid emission rates for CO_2 or NO_X as shown in the following equation:

$E_{GRID} = kWh_{CHP} * ER_{GRID} * 1.114$

Where:

E_{GRID} = Annual grid emissions, lbs
kWh_{CHP} = estimated annual PC 25 C power generated, kWh
ER_{GRID} = emission rates from Table 1-4, lb/kWh
1.114 = Total transmission and distribution losses

Step 3 – Estimate Annual Flare Emissions:

Published EPA AP-42 flare emission factors were used to estimate emissions offsets realized through use of the PC 25 C. AP-42 provides methodology for estimating the NO_X and CO_2 emissions from an enclosed flare based on the amount of gas combusted. The flare emissions will be added to the estimated annual grid emissions to establish the total facility baseline emission estimate. (USEPA 1995)

The approach used to estimate annual flare emissions is similar to the grid emissions estimate. The estimated annual ADG combusted in the flare is reduced by the amount of ADG used to fuel the PC 25 C. The average PC 25 C gas consumption rate measured during the verification testing at full load, along with the projected PC 25 C hours of operation, was used to estimate the amount of ADG used during a typical year of PC 25 C operation.

Appendix D: Average Retail Price of Electricity to Ultimate Customers by End-Use Sector, by State, July 2007 and 2006 (Source: Energy Information Administration) (Cents per kilowatt hour, ¢/kWh)

Census Division and State	Residential		Commercial[1]		Industrial[1]		All Sectors	
	Jul-07	Jul-06	Jul-07	Jul-06	Jul-07	Jul-06	Jul-07	Jul-06
New England	**16.18**	**15.89**	**14.64**	**14.51**	**12.97**	**10.57**	**14.87**	**14.38**
Connecticut	18.33	16.36	15.16	13.89	13.95	11.95	16.31	14.7
Maine	15.02	14.22	12.36	11.91	11	7.59	13.24	11.64
Massachusetts	15.67	16.54	15.26	15.8	13.45	11.15	14.97	15.31
New Hampshire	14.96	14.35	13.39	13.16	12.44	9.89	13.81	13.08
Rhode Island	14.28	15.03	12.89	13.53	12.39	11.69	13.38	13.88
Vermont	14.24	13.63	12.34	11.73	8.86	8.45	12.05	11.55
Middle Atlantic	**14.91**	**14.23**	**14.33**	**12.94**	**8.42**	**7.87**	**13.49**	**12.47**
New Jersey	16.39	14.6	15.12	14.15	13.19	10.45	15.44	13.92
New York	17.24	17.28	16.69	14.61	9.58	9.07	16.1	14.8
Pennsylvania	11.51	11.05	9.48	8.89	7.15	6.8	9.51	9.07
East North Central	**10.11**	**9.66**	**8.6**	**8.46**	**6.13**	**5.67**	**8.36**	**8**
Illinois	10.35	9.2	8.47	8.59	6.78	5.14	8.81	7.89
Indiana	8.26	8.13	7.4	7.14	5.2	5.28	6.75	6.69
Michigan	10.53	10.55	8.91	8.94	6.62	6.44	8.83	8.84
Ohio	10.43	10.01	8.95	8.39	6.06	5.74	8.46	8.1
Wisconsin	10.94	10.64	8.95	8.89	6.62	6.18	8.85	8.63
West North Central	**9.18**	**8.99**	**7.68**	**7.4**	**5.75**	**5.6**	**7.74**	**7.57**
Iowa	9.97	10.1	7.98	7.93	5.5	5.46	7.76	7.86
Kansas	9.05	8.89	7.61	7.53	5.57	5.72	7.69	7.69
Minnesota	9.75	9.5	8.41	7.92	6.43	6.16	8.29	8.02
Missouri	8.8	8.43	7.52	7.1	5.75	5.63	7.76	7.42
Nebraska	8.73	8.6	6.89	6.71	5.31	5	7.03	6.8
North Dakota	8.26	8.12	6.92	6.47	4.66	4.49	6.65	6.39
South Dakota	8.55	8.63	6.82	6.98	5.29	5.16	7.19	7.3
South Atlantic	**10.41**	**10.11**	**8.71**	**8.54**	**5.91**	**5.95**	**8.99**	**8.8**
Delaware	13.64	13.45	11.28	13.2	9.06	4.89	11.68	11.21
District of Columbia	12.72	11.3	12.61	12.94	10.69	9.32	12.46	12.43
Florida	11.18	11.32	9.49	9.71	7.66	7.73	10.27	10.43
Georgia	9.85	9.75	8.13	8.03	5.73	5.87	8.33	8.32
Maryland	13.38	11.43	12.22	11.49	9.79	12.68	12.52	11.58
North Carolina	9.56	9.12	7.66	7.18	5.93	5.66	8.15	7.73
South Carolina	9.34	9.07	7.92	7.69	5.18	5.05	7.54	7.34
Virginia	9.26	8.96	6.43	6.18	4.97	4.76	7.39	7.13
West Virginia	6.81	6.3	5.73	5.41	4.03	3.74	5.36	5.05
East South Central	**8.34**	**8.34**	**7.97**	**7.89**	**5.49**	**5.52**	**7.26**	**7.26**
Alabama	9.28	9.09	8.49	8.32	5.4	5.54	7.67	7.65
Kentucky	7.35	7.23	6.86	6.57	5.36	5.13	6.4	6.19
Mississippi	9.4	9.44	8.7	8.87	5.82	5.96	8.11	8.29
Tennessee	7.7	7.86	7.96	7.98	5.56	5.74	7.16	7.28

West South Central	**11.38**	**11.72**	**9.52**	**9.37**	**7.13**	**7.21**	**9.63**	**9.83**
Arkansas	9.08	9.05	7.02	7.09	5.58	5.9	7.32	7.48
Louisiana	9.7	9.19	9.24	8.76	6.95	6.74	8.71	8.34
Oklahoma	8.94	8.56	7.96	7.62	5.79	5.61	7.87	7.64
Texas	12.51	13.22	10.1	10.02	7.7	7.83	10.48	10.87
Mountain	**9.94**	**9.4**	**7.94**	**7.7**	**6.21**	**5.88**	**8.29**	**7.9**
Arizona	10.35	9.83	8.89	8.33	6.42	6.22	9.34	8.85
Colorado	9.03	9.14	7.1	7.48	5.97	6.12	7.54	7.75
Idaho	6.97	6.28	5.39	5.01	4.25	3.88	5.28	4.82
Montana	9.32	8.6	8.34	7.23	5.34	4.88	7.67	6.82
Nevada	12.12	10.93	10.12	10.03	10.28	9.66	11.08	10.33
New Mexico	9.32	9.15	7.62	7.54	5.83	5.31	7.63	7.39
Utah	8.86	8.08	6.8	6.3	5.31	4.84	7.19	6.6
Wyoming	8.06	8.4	6.2	6.29	4.12	4.06	5.3	5.33
Pacific Contiguous	**12.88**	**14.04**	**12.51**	**13.36**	**8.58**	**8.16**	**11.86**	**12.51**
California	15	16.65	14.4	15.71	11.02	10.94	14.03	15.22
Oregon	8.81	7.48	7.17	6.86	5.08	4.34	7.19	6.32
Washington	7.61	6.77	6.55	6.34	4.85	4.25	6.49	5.87
Pacific Noncontiguous	**21.57**	**21.61**	**17.96**	**18.15**	**17.17**	**17.56**	**18.79**	**19.01**
Alaska	15.7	15.84	12.01	12.01	12.57	12.53	13.23	13.31
Hawaii	24.59	24.62	22.38	22.67	18.76	19.03	21.72	21.9
U.S. Total	**11.06**	**10.97**	**10.09**	**9.86**	**6.75**	**6.5**	**9.67**	**9.49**

This is the most recent statistics published as of Nov. 1st 2007.

Appendix E: Average Retail Price of Natural Gas to Ultimate Customers by End-Use Sector, by State, July 2007 (Source: Energy Information Administration) (Dollars per Thousand Cubic Feet, $/kcf)*

	Residential	**Commercial**	**Industrial**
State	**Jul-07**	**Jul-07**	**Jul-07**
U.S.	**16.65**	**11.63**	**7.58**
Alabama	22.91	14.48	8.46
Alaska	9.77	6.27	4.18
Arizona	23.36	13.45	11.71
Arkansas	18.97	10.66	9.21
California	12.88	10.85	9.70
Colorado	NA	7.61	7.19
Connecticut	20.92	13.45	10.26
Delaware	23.04	16.66	9.72
District of Columbia	18.95	12.61	NA
Florida	24.20	13.55	10.29
Georgia	28.63	14.78	9.15
Hawaii	34.26	28.52	18.38
Idaho	12.62	11.00	9.22
Illinois	15.48	13.45	13.48
Indiana	17.51	11.81	8.91
Iowa	18.14	11.45	8.34
Kansas	19.54	15.22	6.97
Kentucky	17.72	12.63	8.17
Louisiana	17.57	11.39	7.72
Maine	18.84	14.13	13.84
Maryland	NA	11.81	11.28
Massachusetts	18.30	13.20	13.78
Michigan	14.98	10.38	10.21
Minnesota	12.32	9.46	7.14
Mississippi	11.25	10.11	8.33
Missouri	22.19	13.38	11.07
Montana	12.86	12.12	11.74
Nebraska	17.20	9.65	8.40
Nevada	17.19	12.37	12.08
New Hampshire	19.52	15.24	12.69
New Jersey	16.50	11.82	10.08
New Mexico	16.04	10.95	8.58
New York	19.57	10.74	11.34
North Carolina	22.47	13.43	9.88
North Dakota	14.31	8.92	6.70
Ohio	16.85	11.26	11.77
Oklahoma	18.06	13.83	11.46
Oregon	17.38	12.78	9.28
Pennsylvania	20.79	13.26	11.22
Rhode Island	19.75	18.49	12.96

South Carolina	NA	13.06	9.09
South Dakota	15.05	9.37	8.27
Tennessee	17.93	13.23	8.83
Texas	NA	10.42	6.91
Utah	10.57	8.10	5.80
Vermont	21.62	14.16	9.25
Virginia	22.17	11.80	9.78
Washington	16.98	13.33	9.60
West Virginia	19.98	14.38	8.69
Wisconsin	15.34	10.33	8.88
Wyoming	12.10	8.05	5.89
U.S.	**16.65**	**11.63**	**7.58**

This is the most recent statistics published as of Nov. 1st 2007.

***For the purpose of this thesis, natural gas will be measured in MMBTU for direct conversion purposes. The conversion factor of 1 thousand cubic feet (kcf) = 1.013 MMBTU (www.doe.gov) will be utilized for this conversion.**

For our cost assessment, the most important value on the above table is the average cost of natural gas to large industrial customers in the United States ($7.58 per kcf). To convert this figure to $ per MMBTU:

$7.58/kcf x 1 kcf/1.013 MMBTU = $7.48/MMBTU

This page was left intentionally blank.

Appendix F: State and Federal Anaerobic Digestion Gas Incentive Programs: Anaerobic Digestion Gas Grant Programs (Source: Database of State Incentives for Renewables & Efficiency (DSIRE))

State/Territory	Abbrev.	Grant Program?	Program	Organization	Details
CONNECTICUT	CT	Y	CCEF - On-Site Renewable DG Program	Connecticut Clean Energy Fund	Amount: Varies by project Maximum Amount: $4 million per project (plus potential additional production incentive for projects installed in southwestern Connecticut) Equipment Requirements: Minimum system capacity of 10 kW; systems must be commercially available, and must have warrantees, spare parts and service commensurate with commercial status
CONNECTICUT	CT	Y	CCEF - Project 100 Initiative	Connecticut Clean Energy Fund	$50,000 (Round 2 proposals) for project 100 Initiative Projects, purchasing of at least 100 MW of electricity from projects, premium up to 5.5¢ per kWh.
CONNECTICUT	CT	Y	DPUC - Capital Grants for Customer-Side Distributed Resources	Connecticut Department of Public Utility Control	CHP Cogeneration, Amount: $450/kW for baseload projects ($500/kW if sited in southwest CT); $200/kW for emergency generators ($250/kW if sited in southwest CT) Maximum Amount: $500/kW Equipment Requirements: 65 MW maximum capacity
CONNECTICUT	CT	Y	OPM - New Energy Technology Program	Connecticut Office of Policy and Management	Research, Development and Improvement, Maximum Amount: $10,000 Equipment Requirements: Measures must be in the prototype stage or pre-commercial stage
DELAWARE	DE	Y	Research and Development Grants	Delaware Department of Natural Resources and Environmental Control	Maximum Amount: 35% cost of qualifying projects, $250,000 per project
DISTRICT OF COLUMBIA	DC	Y	Renewable Energy Demonstration Project (REDP)	District Department of the Environment	Varies by Project.

FEDERAL	**FED**	Y	USDA Renewable Energy Systems and Energy Efficiency Improvements Program	U.S. Department of Agriculture (USDA)	Amount: Grants: 25% of eligible project costs; Guaranteed loans: 50% of eligible project costs Max. Limit: Grants: $500,000 per renewable-energy project; Guaranteed loans: $10 million
FLORIDA	FL	Y	Renewable Energy Technologies Grants Program	Department of Environmental Protection	Varies by Project.
ILLINOIS	IL	Y	Illinois Clean Energy Community Foundation Grants	Illinois Clean Energy Community Foundation	Private, Varies by Project.
INDIANA	IN	Y	Biomass Feasibility Study Grant Program	Indiana Office of Energy and Defense Development	Amount: 50% of costs associated with the study Maximum Amount: $25,000
IOWA	IA	Y	Grants for Energy Efficiency and Renewable Energy Research	Iowa State University, Iowa Energy Center	State Grant Program, Varies by Project.
MAINE	ME	Y	Voluntary Renewable Resources Grant	Maine Public Utilities Commission	Amount: Varies by project Maximum Amount: $50,000; 50% of project cost Equipment Requirements: Maximum capacity: 100 MW
MASSACHUSETTS	MA	Y	MTC - Clean Energy Pre-Development Financing Initiative (Grants)	Massachusetts Technology Collaborative	State Grant Program, Amount: Varies by Project. Maximum Amount: $50,000
MASSACHUSETTS	MA	Y	MTC - Large Onsite Renewables Initiative (LORI) Grants	Massachusetts Technology Collaborative	Amount: Varies by solicitation Maximum Amount: Feasibility Grants are capped at $40,000 with an applicant cost share of 15% Photovoltaic Design & Construction Grants are capped at the lesser of $250,000 or 75% of actual costs Non Photovoltaic Design & Construction Grants are capped at the lesser of $400,000 or 75% of actual costs
MICHIGAN	MI	Y	Energy Efficiency Grants	Michigan Public Service Commission	Varies by Project.
MINNESOTA	MN	Y	Minnesota Power - Power Grant Program	Minnesota Power Grant Program	Amount: Grants are ranked and awarded based on least grant cost per kW (annually) and/or kWh (lifetime). Max. Limit: 0 to 100 kW $10,000; 101 to 300 kW $25,000; Over 300 kW $50,000.

MINNESOTA	MN	Y	Xcel Energy - Renewable Development Fund Grants	Xcel Energy	Utility Grant Program, Amount: Varies by Project. Max. Limit: Individual projects in the Energy Production category: $2 million (2007 solicitation); individual projects in the R&D category: $1 million (2007 solicitation)
NEW YORK	NY	Y	NYSERDA - Distributed Generation as Combined Heat and Power (DG-CHP)	New York State Energy Research and Development Authority	Amount: Varies Maximum Amount: Category A (Demonstration): 30-50% of project cost up to $2 millionCategory B (Recommisioning Studies): 50% of project cost up to $75,000Category C (Technology Transfer): 75% of project cost up to $100,000 Equipment Requirements: Category A: The DG-CHP system must be designed and installed for grid independent operation and be able to supply priority loads during a grid outage;Must have a projected overall thermal efficiency of 60% or more; and Meet an air emission limit of of no more than 1.6 lb NOx/MWhProject Review/Certification: Category A: Commissioning requires a Project Installation Report;NYSERDA may inspect system any time up to 4 years after commissioning
NEW YORK	NY	Y	NYSERDA - Distributed Generation as Combined Heat and Power (DG-CHP)	New York State Energy Research and Development Authority	Varies by Project.
OHIO	OH	Y	ODOD - Energy Loan Fund (ELF) Grants - Distributed Energy and Renewable Energy	Ohio Department of Development	Amount: Varies by grant type and technology type Maximum Amount: $150,000

OREGON	OR	Y	Energy Trust - Open Solicitation Program	Energy Trust of Oregon	New, commercial technologies in established applications; Existing commercial technologies in new applications; Projects that can be replicated elsewhere, thereby helping to build renewable energy markets. Must be in or able to deliver power to the service territory of either Portland General Electric or Pacific Power; off grid projects are not eligible.
PENNSYLVANIA	PA	Y	Metropolitan Edison Company SEF Grants (FirstEnergy Territory)	Berks County Community Foundation	Local Grant Program, Varies according to project Max. Limit: $25,000
PENNSYLVANIA	PA	Y	Penelec SEF of the Community Foundation for the Alleghenies Grant Program (FirstEnergy Territory)	Community Foundation of the Alleghenies	Local Grant Program, Amount: Varies according to project Max. Limit: Loans typically do not exceed $500,000; Grants typically do not exceed $25,000
PENNSYLVANIA	PA	Y	Pennsylvania Energy Development Authority (PEDA) - Grants	Pennsylvania Department of Environmental Protection	Amount: Varies Maximum Amount: $1 million per project
PENNSYLVANIA	PA	Y	Sustainable Development Fund Grant Program (PECO Territory)	Sustainable Development Fund	Local Grant Program, Amount: $25,000 average Max. Limit: Up to 75% of the costs, with 25% being covered by the applicant
PENNSYLVANIA	PA	Y	West Penn Power SEF Grant Program	The Energy Institute	Local Grant Program, Max. Limit: Varies by proposal Terms: Varies by proposal
TENNESSEE	TN	Y	Tennessee Clean Energy Technology Grant	Tennessee Department of Economic & Community Development	Amount: 40% of Project Maximum Amount: $75,000
VERMONT	VT	Y - agricultural	CVPS - Biomass Grants	Central Vermont Public Service Corporation (CVPS)	Amount: Incentive packages issued on case-by-case basis
WISCONSIN	WI	Y	Focus on Energy - Renewable Energy Grant Programs	Focus on Energy	Amount: Varies by technology and estimated energy production Maximum Amount: $260,000 to any individual or business during each fiscal year Equipment Requirements: 2-year installation warranty; 1-year equipment warranty; A system performance meter must be included in electric generating systems

WISCONSIN	WI	Y	We Energies - Direct Financial Incentives for Not-for-Profits	We Energy	Amount: $10,000 - $100,000 Max. Limit: $100,000 Terms: Systems must be manufactured and installed in compliance with the latest edition of the National Electric Code. Systems must be installed by a "Full-Service Installer" approved by Focus on Energy. PV and wind-energy projects must undergo a site-assessment prior to proposal submission.
REGIONAL					
Northwest United States		Y	BEF - Renewable Energy Grant	Bonneville Environmental Foundation	Private grants, Up to 33% of total capital costs
Northwest United States		Y	NorthWestern Energy - USB Renewable Energy Fund	NorthWestern Energy	Utility Grant Program, Amount: PV: $3.50/watt, up to a maximum of $7,000 Wind: $2/watt, up to a maximum of $10,000, Others vary by project.

States with Grant Programs	**26**
States with ADG Grants	**15**
Federal Grants	**1**

This is the most recent statistics published as of Nov. 1st 2007.

Appendix G: State and Federal Anaerobic Digestion Gas Incentive Programs: Anaerobic Digestion Gas Loan Programs

(Source: Database of State Incentives for Renewables & Efficiency (DSIRE))

State/Territory	Abbrev.	Loan Program?	Program	Organization	Details
ALASKA	AK	Y	Power Project Loan Fund	Alaska Industrial Development and Export Authority (AIDEA)	Amount: Varies Terms: Interest rate tied to municipal bonds
COLORADO	CO	Y	Gunnison County Electric - Renewable Energy Resource Loan	Gunnison County Electric Association, Inc.	Utility Loan Program, Up to $25,000 for 10 years
CONNECTICUT	CT	Y	CCEF - Operational Demonstration Program	Connecticut Clean Energy Fund (CCEF)	Amount: Varies Maximum Amount: $750,000
CONNECTICUT	CT	Y	DPUC - Low-Interest Loans for Customer-Side Distributed Resources	Connecticut Department of Public Utility Control	Amount: Varies Terms: Fixed interest rate, no more than prime rate (actual rate will be determined at time of application)
FEDERAL	**FED**	Y	USDA Renewable Energy Systems and Energy Efficiency Improvements Program	U.S. Department of Agriculture (USDA)	Amount: Grants: 25% of eligible project costs; Guaranteed loans: 50% of eligible project costs Max. Limit: Grants: $500,000 per renewable-energy project; Guaranteed loans: $10 million
IOWA	IA	Y	Alternate Energy Revolving Loan Program	Iowa State University	Amount: 50% of financed project cost Maximum Amount: $250,000 Terms: 0% interest Maximum term of 20 years
MASSACHUSETTS	MA	Y	MTC - Clean Energy Pre-Development Financing Initiative (Loans)	Massachusetts Technology Collaborative	Amount: Varies Maximum Amount: $250,000
MINNESOTA	MN	Y - agricultural	Agricultural Improvement Loan Program	Minnesota Department of Agriculture	Amount: RFA provides up to 45% of loan Maximum Amount: RFA provides up to $200,000 of loan principal Terms: Maximum term of 10 years
MINNESOTA	MN	Y - agricultural	Methane Digester Loan Program	Minnesota Department of Agriculture	Amount: RFA participation limited to 45% of loan principal Maximum Amount: RFA can provide up to $250,000 of loan principal Terms: 10 year maximum
MINNESOTA	MN	Y - agricultural	Value-Added Stock Loan Participation	Minnesota Department of Agriculture	Amount: RFA provides up to 45% of loan Maximum Amount: RFA provides up to

			Program		$40,000 of loan principal Terms: Maximum term of eight years
MISSISSIPPI	MS	Y	Energy Investment Loan Program	Mississippi Development Authority	Applicable Sectors: Commercial, Industrial Amount: $15,000 - $300,000 Maximum Amount: $300,000 Terms: 3% below prime rate; 7-year payback
MONTANA	MT	Y	Alternative Energy Revolving Loan Program	Montana Department of Environmental Quality	Amount: Varies Maximum Amount: $40,000 Terms: Up to 10 years; 5% interest rate for 2006
PENNSYLVANIA	PA	Y	Metropolitan Edison Company SEF Loans (FirstEnergy Territory)	Berks County Community Foundation	Local Loan Program, Amount: Varies according to project Max. Limit: $500,000 Terms: Vary according to project
PENNSYLVANIA	PA	Y	Penelec SEF of the Community Foundation for the Alleghenies Loan Program (FirstEnergy Territory)	Community Foundation of the Alleghenies	Local Loan Program, Amount: Varies according to project Terms: Vary according to project
PENNSYLVANIA	PA	Y	Pennsylvania Energy Development Authority (PEDA) - Loans and Loan Guarantees	Pennsylvania Department of Environmental Protection	Amount: Varies Maximum Amount: Loans: $1 million Loan guarantees: $500,000
PENNSYLVANIA	PA	Y	SEF of Central Eastern Pennsylvania Loan Program (PP&L Territory)	Sustainable Energy Fund of Central Eastern PA	Amount: Varies by project Terms: Vary by project
PENNSYLVANIA	PA	Y	Sustainable Development Fund Commercial Financing Program (PECO Territory)	Sustainable Development Fund	Local Loan Program, Amount: $25,000 to $250,000 Terms: 5% to 6.5%; Up to 10 year terms
PENNSYLVANIA	PA	Y	West Penn Power SEF Commercial Loan Program	The Energy Institute	Amount: Varies according to project Terms: Vary according to project
SOUTH CAROLINA	SC	Y	Renewable Energy Revolving Loan Program	South Carolina Energy Office	Maximum Amount: $250,000 (The loan may not provide more than 50% of the project cost) Terms: Loans must be approved by the South Carolina Renewable Energy Oversight Committee

States with Loan	**30**

Programs	
States with ADG Loans	10
Federal Loans	1

This is the most recent statistics published as of Nov. 1st 2007.

Appendix H: State and Federal Anaerobic Digestion Gas Incentive Programs: Anaerobic Digestion Gas Bond Programs

(Source: Database of State Incentives for Renewables & Efficiency (DSIRE))

State/Territory	Abbre.	Bond Program?	Program	Organization	Details
FEDERAL	**FED**	Y	Clean Renewable Energy Bonds (CREBs)	Internal Revenue Service	Amount: Varies, Terms: Fixed Interest Rates
IDAHO	ID	Y	Renewable Energy Project Bond Program	Idaho Energy Resources Authority	The Authority was created to finance the construction of electric generation and transmission projects by electric utilities. SB 1192 extends the financing opportunities to independent renewable energy producers.
NEW MEXICO	NM	Y	Energy Efficiency & Renewable Energy Bond Program	New Mexico Finance Authority	Amount: Varies Maximum Amount: $20 million in bonds outstanding at any one time

States with Bond Programs	**3**
States with ADG Bonds	**2**
Federal Bonds	**1**

This is the most recent statistics published as of Nov. 1st 2007.

Appendix I: State and Federal Anaerobic Digestion Gas Incentive Programs: Anaerobic Digestion Gas Corporate Tax Credit Incentives Programs

(Source: Database of State Incentives for Renewables & Efficiency (DSIRE))

State/Territory	Abbrev.	Tax Credit Program?	Program	Organization	Details
FEDERAL	**FED**	Y	Business Energy Tax Credit	Internal Revenue Service	Amount: For equipment placed in service from January 1, 2006 until December 31, 2008, the credit is 30% for solar, solar hybrid lighting, and fuel cells, and 10% for microturbines. The geothermal credit remains at 10%. Maximum Incentive: $500 per 0.5 kW for fuel cells; $200 per kW for microturbines; no maximum specified for other technologies Eligible System Size: Microturbines less than 2 MW; fuel cells at least 0.5 kW
FEDERAL	**FED**	Y	Modified Accelerated Cost-Recovery System (MACRS)	Internal Revenue Service	Under the Modified Accelerated Cost-Recovery System (MACRS), businesses can recover investments in certain property through depreciation deductions. The MACRS establishes a set of class lives for various types of property, ranging from three to 50 years, over which the property may be depreciated.
FEDERAL	**FED**	Y	Renewable Electricity Production Tax Credit	Internal Revenue Service	Amount: 1.9¢/kWh for wind, geothermal, closed-loop biomass; 1.0¢/kWh for others. Applies to first 10 years of operation.
FLORIDA	FL	Y	Renewable Electricity Production Tax Credit	Florida Department of Revenue	Amount: $0.01/kWh for electricity produced from 1/1/2007 through 6/30/2010 Maximum Incentive: No maximum specified for individual projects; Maximum of $5 million per state fiscal year for all credits under this program
IOWA	IA	Y	Renewable Energy Production Tax Credits (Corporate)	Iowa Utilities Board	Amount: 1.5¢/kWh (IA Code § 476C) or 1.0¢/kWh (IA Code § 476B) Maximum Incentive: 1.5¢/kWh (IA Code § 476C)

KENTUCKY	KY	Y	Tax Credit for Renewable Energy Facilities	Office of Energy Policy	Amount: 100% State Income Tax 4% wage assessment Maximum Incentive: 50% of capital investment; negotiated incentive package may not exceed 25 years Eligible System Size: >50 kW for solar power, >1 MW for wind power, biomass, landfill gas, hydropower or similar resource
MARYLAND	MD	Y	Clean Energy Production Tax Credit - Corporate	Comptroller of MarylandRevenue Administration Division	Amount: 0.85¢/kWh (0.5¢/kWh for co-fired electricity) Maximum Incentive: $2.5 million (total credit during five-year period)
MONTANA	MT	Y	Alternative Energy Investment Corporate Tax Credit	Montana Department of Revenue	Amount: 35%; participant investment must be greater than or equal to $5,000 Maximum Incentive: Not specified
NEBRASKA	NE	Y	Renewable Energy Tax Credit (Corporate)	Nebraska Department of Revenue	Amount: Credits are available for a 10-year period: $0.00075/kWh for electricity generated through 9/30/2007; $0.001/kWh from 10/1/2007 - 12/31/2009; $0.00075/kWh from 1/1/2010 - 12/31/2012; $0.0005/kWh from 1/1/2013 - 12/31/2017 Maximum Incentive: Total amount of tax credits that may be used by all taxpayers is limited to $750,000
NEW MEXICO	NM	Y	Renewable Energy Production Tax Credit (Corporate)	New Mexico Energy, Minerals and Natural Resources Department	Amount: $0.01/kWh for wind and biomass $0.027/kWh (average) for solar (see below) Maximum Incentive: Wind and biomass: First 400,000 MWh annually for 10 years (i.e. $4,000,000/year) Solar electric: First 200,000 MWh annually for 10 years (annual amount varies) Statewide cap: 2,000,000 MWh plus an additional 500,000 MWh for solar electric Minimum of 1 MW capacity per facility
NORTH CAROLINA	NC	Y	Renewable Energy Tax Credit - Corporate	North Carolina Solar Center	Amount: 35% Maximum Incentive: $2.5 million per installation
OHIO	OH	Y	Energy Conversion Facilities Corporate Tax Exemption	Ohio Department of Development	Amount: 100% Exemption Maximum Incentive: None
OREGON	OR	Y	Business Energy Tax Credit	Oregon Department of Energy	Amount: 50% of eligible project costs, distributed over five years (10% per year) Maximum Incentive: $10 million

SOUTH CAROLINA	SC	Y	Biomass Energy Tax Credit	South Carolina Energy Office	Amount: 25% of eligible costs Maximum Incentive: $650,000 per year; credit may not exceed 50% of tax liability
UTAH	UT	Y	Renewable Energy Systems Tax Credit - Corporate	State Energy Program	Amount: Residential: 25%Commercial wind, geothermal electric, and biomass systems 660 kW or greater: 0.35¢/kWh ($0.0035/kWh) for 4 yearsOther commercial systems: 10% Maximum Incentive: Residential: $2,000Commercial wind, geothermal electric, and biomass systems 660 kW or greater: no limitOther commercial systems: $50,000

States with Tax Credits	**22**
States with ADG Tax Credits	**12**
Federal Tax Credits	**3**

This is the most recent statistics published as of Nov. 1st 2007.

Appendix J: State and Federal Anaerobic Digestion Gas Incentive Programs: Anaerobic Digestion Production Incentives Programs

(Source: Database of State Incentives for Renewables & Efficiency (DSIRE))

State/Territory	Abbrev.	ADG Incentive?	Program	Organization	Details
ALASKA	AK	Y	Golden Valley Electric Association - Sustainable Natural Alternative Power (SNAP) Program	Golden Valley Electric Association	Max Incentive $1.50/kWh, max sytem capacity 25/kW
CALIFORNIA	CA	Y	SCE - Biomass Standard Contract	Southern California Edison Company (SCE)	$80.80/MWh to $93.93/MWh (varies by term length and year of production)
CALIFORNIA	CA	Y	Supplemental Energy Payments (SEPs)	California Energy Commission	Above-market costs as compared to a market price referent (subject to determination by the California Public Utilities Commission and the California Energy Commission)
FEDERAL	FED	Y	Renewable Energy Production Incentive	U.S. Department of Energy	1.5 cents per kWh (indexed for inflation)
MINNESOTA	MN	Y	Minnesota - Renewable Energy Production Incentive	Minnesota Department of Commerce	1.0¢-1.5¢/kWh
NEVADA	NV	Y	Portfolio Energy Credits	Public Utilities Commission of Nevada	Varies; Higher value for solar PECs than other technologies
NEW YORK	NY	Y	NYSERDA - Anaerobic Digester Gas-to-Electricity Program	New York State Energy Research and Development Authority	$500/kW capacity incentive for new equipment AND $0.10/kWh production payment for new systems OR $0.02/kWh maintenance payment on production from systems installed or substantially upgraded since Jan. 1, 2003. Maximum Incentive: $1 million (combined production and capacity incentives) Capacity incentive capped at lesser of $350,000 or 50% of project cost
NORTH CAROLINA	NC	Y	NC GreenPower Production Incentive	NC GreenPower	Varies by technology and customer demand for NC GreenPower
SOUTH CAROLINA	SC	Y	Biomass Energy Production Incentive	South Carolina Energy Office	$.01 per kWh / $.09 per therm Maximum Incentive: $100,000 per fiscal year per taxpayer; $2.1 million per fiscal year for all taxpayers
VERMONT	VT	Y	CVPS - Biomass Electricity Production Incentive	Central Vermont Public Service Corporation	95% of Locational Marginal Price of generation published by ISO New England + $0.04 per kWh

WASHINGTON	WA	Y	Okanogan County PUD - Sustainable Natural Alternative Power Program	Okanogan County Public Utility District	Varies Maximum Incentive: $1.00/kWh Terms: Systems up to 100 kW can participate, but the incentive will be adjusted to that of a 25 kW system
WYOMING	WY	Y	We Energies - Biogas Buy-Back Rate	We Energies	$0.08 per kilowatt-hour (8.0¢/kWh) for on-peak generation; $0.049 per kilowatt-hour (4.9¢/kWh) for off-peak generation Terms: Available to systems up to 800 kW in capacity; maximum aggregate capacity limit of 10 MW

States with Production Incentives	**26**
States with ADG Production Incentives	**10**
Federal Incentives	**1**

Appendix K: Cost Assessments of Installing and Utilizing the Modified PC 25 C Fuel Cell Power Plants at Wastewater Treatment Plants

FC Electricity Output (kW)	FC Heat Output (BTU)	Thermal Efficiency (%)	FC Capacity Factor (%)	FC Availability (%)	FC Cost ($/kW)	FC Installation Cost ($/kW)	GPU Cost ($/kW)	Incetives/Grants ($/kW)
200	900000	85	63	89	3500	1250	150	1000

Operating & Maintenance Cost ($/kWh)	Large Maintenance Projects ($)	Frequency of maintenance project (yrs)	Effective Life of Equipment (yrs)	Cost of Electricity ($/kWh)	Cost of Natural Gas ($/MMBTU)	10% Carrying Charge for Natural Gas	Hours of Operation per Day	Days of Operation Per Year
0.0225	250000	7	20	0.0675	7.48	0.748	24	365

Initial Cost = FC Electricity Output (FC Cost + FC Installation Cost + GPU Cost - Incentives/Grants)

Initial Cost ($) 780000

Yearly Electricity Generation = FC Energy Output x Hours of Operation per Day x Days of Operation per Year x FC Capacity Factor x FC Availability

Yearly Electricity Generation (kWh) 982346.4

Yearly Electricity Savings = Yearly Electricity Generation x Cost of Electricity

Yearly Electricity Savings ($) 66308.382

Yearly O&M Costs = Yearly Electricity Generation x Operating and Maintenance Costs

Yearly O&M Costs (S) 22102.794

Net Cash Flow Per Year = Yearly Electricity Savings - Yearly O&M Costs

Yearly Electric Savings Only	**Net Cash Flow ($)**	44205.588	**all years (1-20) except large maintenance years**

Yearly Heat Generation = FC Heat Output x Hours of Operation per Day x Days of Operation per Year x Capacity Factor x Availability x Thermal Efficiency

Yearly Heat Generation (BTU)	3757474980		**Yearly Heat Generation (MMBTU)**	3757.47498

Yearly Savings from Heat Generated = Yearly Heat Generation x (Cost of Natural Gas+Natural Gas Carrying Charge)

Yearly Savings from Heat Generated ($)	30916.50414

Net Cash Flow Per Year = Yearly Electricity Savings + Yearly Heat Savings - Yearly O&M Costs

Yearly Electric and Heat	**Net Cash Flow ($)**	75122.09214

ADG Fuel Cell Cash Flow (Electricity Only) NPV	**from next page** **$ (597,775.25)**	**ADG Fuel Cell Cash Flow (Electricity and Heat) NPV**	**from next page** **$ (334,565.62)**

Appendix J: Cost Assessments of Installing and Utilizing the Modified PC 25 C Fuel Cell Power Plants at Wastewater Treatment Plants (Continued)

ADG Fuel Cell Cost Assessment (Electricity Only)

Time Period (T) year	Net Cash Flows (CF)*	Discount Rate	Discounted Cash Flow
1	44,205.59	10%	40,186.90
2	44,205.59	10%	36,533.54
3	44,205.59	10%	33,212.31
4	44,205.59	10%	30,193.01
5	44,205.59	10%	27,448.19
6	44,205.59	10%	24,952.90
7	(205,794.41)	10%	(105,605.07)
8	44,205.59	10%	20,622.23
9	44,205.59	10%	18,747.48
10	44,205.59	10%	17,043.17
11	44,205.59	10%	15,493.79
12	44,205.59	10%	14,085.26
13	44,205.59	10%	12,804.78
14	(205,794.41)	10%	(54,192.10)
15	44,205.59	10%	10,582.47
16	44,205.59	10%	9,620.42
17	44,205.59	10%	8,745.84
18	44,205.59	10%	7,950.76
19	44,205.59	10%	7,227.97
20	44,205.59	10%	6,570.88
	Gross Present Value (GPV)		**182,224.75**
	Initial Investment		**780,000.00**
	Net Present Value (NPV)		**(597,775.25)**
	Internal Rate of Return after 20 years		**-6%**

ADG Fuel Cell Cost Assessment (Electricity and Heat)

Time Period (T) year	Net Cash Flows (CF)	Annual Discount Rate	Discounted Cash Flow
1	$75,122	10%	68,292.81
2	$75,122	10%	62,084.37
3	$75,122	10%	56,440.34
4	$75,122	10%	51,309.40
5	$75,122	10%	46,644.91
6	$75,122	10%	42,404.46
7	($174,878)	10%	(89,740.02)
8	$75,122	10%	35,045.01
9	$75,122	10%	31,859.10
10	$75,122	10%	28,962.82
11	$75,122	10%	26,329.84
12	$75,122	10%	23,936.21
13	$75,122	10%	21,760.19
14	($174,878)	10%	(46,050.82)
15	$75,122	10%	17,983.63
16	$75,122	10%	16,348.76
17	$75,122	10%	14,862.51
18	$75,122	10%	13,511.37
19	$75,122	10%	12,283.06
20	$75,122	10%	11,166.42
	Gross Present Value (GPV)		**445,434.38**
	Initial Investment		**780,000.00**
	Net Present Value (NPV)		**(334,565.62)**
	Internal Rate of Return after 20 years		**3%**

This page was left intentionally blank.